<table>
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<tr>
<th>No</th>
<th>Date</th>
<th>Subject</th>
<th>Detailed Content</th>
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<td>1</td>
<td>19.10</td>
<td>Introduction</td>
<td>Introduction, optical measurements, shape measurements, errors, definition of the meter, sampling theorem</td>
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<td>Basics, polarization, wave aberrations, PSF, OTF</td>
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<td>Sensors</td>
<td>Introduction, basic properties, CCDs, filtering, noise</td>
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<td>Moire principle, illumination coding, fringe projection, deflectometry</td>
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<td>Introduction, interference, types of interferometers, miscellaneous</td>
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<td>Spatial and temporal coherence, speckle, properties, speckle metrology</td>
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<td>21.12</td>
<td>Holography</td>
<td>Introduction, holographic interferometry, applications, miscellaneous</td>
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<td>11</td>
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<td>Measurement of basic system properties</td>
<td>Basic properties, knife edge, slit scan, MTF measurement</td>
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<td>Introduction, algorithms, practical aspects, accuracy</td>
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<td>Metrology of aspheres and freeforms</td>
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<td>Principle of OCT, tissue optics, Fourier domain OCT, miscellaneous</td>
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<td>15</td>
<td>08.02</td>
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<td>Principle, resolution and PSF, microscopy, chromatical confocal method</td>
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Content

- Introduction
- Holographic setups
- Digital holography
- Holographic interferometry
- Miscellaneous
Basic Idea

- Photography: recording of intensity
  - Holography: recording of amplitude and phase

- Phase can typically not be coded with the help of a reference wave and interference, it is coded as intensity modulation

- Properties:
  - high accuracy, more sensitive
  - hologram corresponds to a diffractive element
  - each partial area of the hologram contains the full information
  - due to large angles, the fringe density is high, the fringe period is in the range of the wavelength (0.5 \( \mu \text{m} \))

- Full information of the object allows for several applications:
  - 3D shape measurement
  - 3D imaging with depth perception
  - interferometric comparison possible to investigate small changes
  - digital substitution of hologram generation and image formation possible (today)

- History:
  - First idea by Gabor, 1948, Nobel price in 1971
  - poor quality, inline with overlayed images
  - Leith / Upatnieks, 1962
Recording a Hologram

- generation of an interferogram
- one wave codes the object shape
- recording the interferogram in a photoplate or CCD: hologram
- a finite thickness of the recording medium creates a 3D information

Ref: R. Kowarschik
Reconstructing the Object

- Illuminating the hologram by the same reference wave
- With special tricks, the object wave can be reconstructed
- Typically a twin images and/or higher diffraction orders must be suppressed

Ref: R. Kowarschik
Holographic Imaging

photography  hologram  reconstructed sample

Ref: W. Osten
Holographic Principle

- Object wave
- Reference wave
- Total wave in hologram plane, intensity
- Reconstruction (linear transmission $T \sim I_H$)
- Interpretation of the 3 terms:
  1. reference wave in 0th order direction
  2. virtual object wave in 1st diffraction order direction
  3. real object in the -1st diffraction order direction

\[ \vec{E}_O = E_O \cdot e^{i\theta} \]
\[ \vec{E}_R = E_R \cdot e^{i\phi} \]
\[ I_H = \left| \vec{E}_O + \vec{E}_R \right|^2 = \vec{E}_O \vec{E}_O^* + \vec{E}_R \vec{E}_R^* + \vec{E}_O \vec{E}_R^* + \vec{E}_R \vec{E}_O^* \]
\[ I_H = \left| \vec{E}_O \right|^2 + \left| \vec{E}_R \right|^2 + \vec{E}_O \vec{E}_R \cdot 2 \cos(\theta - \phi) \]
\[ E_H = I_H \vec{E}_R = \left[ \vec{E}_O^2 + \vec{E}_R^2 + \vec{E}_O \vec{E}_R \cdot \left( e^{i(\theta-\phi)} + e^{-i(\theta-\phi)} \right) \right] \cdot \vec{E}_R e^{i\phi} \]
\[ = \left( \vec{E}_O^2 + \vec{E}_R^2 \right) \cdot \vec{E}_R e^{i\phi} + \vec{E}_O \vec{E}_R e^{i\theta} + \vec{E}_O \vec{E}_R e^{i(2\phi-\theta)} \]

Ref.: H. Naumann
Holography

- Recording

- Reconstruction

- Three terms:

\[ E_H = \bar{E}_O \bar{E}_R^2 e^{i\theta} + \bar{E}_O \bar{E}_R^2 e^{i(2\phi - \theta)} + \left( \bar{E}_O^2 + \bar{E}_R^2 \right) \cdot \bar{E}_R e^{i\phi} \]
Fresnel Zone Plate

- Simple hologram:
  - interference between a plane wave and a spherical wave (point object)
  - hologram: Fresnel zone plate

\[ t(x, y) = A + Be^{\frac{i\pi}{\lambda z}(x^2+y^2)} - Be^{\frac{-i\pi}{\lambda z}(x^2+y^2)} \]

- In the hologram reconstruction with a plane wave:
  1st and -1st diffraction order forms twin images, real and virtual

Ref: T.-J. Poon
Classification of Holograms

- Reflection / transmission
dispersive effects in case of transmission

- Amplitude / phase modulation
higher efficiencies for purely phase changes

- Thin / thick hologram
thin: multiple diffraction orders
thick: Bragg condition, only one diffraction order
smooth transition in between possible

- Surface / volume grating

- on-axis / off-axis
angle between object and reference beam
separation of orders easier in off-axis case

- Binary / digital / analog
amplitude modulation continuous and smooth or with only 2 levels (b/w)
different diffraction efficiencies

- Optical / computational
diffraction pattern physical obtained by interference or calculated

- Setup geometry
Fourier / Fresnel / imaging
Fourier is 2D in infinity with a 2f-lens imaging
Holography

- Thin plane hologram typically higher orders are observed

Ref: R. Kowarschik
Holography

- Thick volume hologram signal and recording comes from the same side.
  Higher orders are suppressed due to the Bragg condition.

Ref: R. Kowarschik
Holography

- Thick volume hologram signal and recording comes from different sides.
  Higher orders are suppressed due to the Bragg condition.

Ref: R. Kowarschik
Thin vs Thick Holograms

- A hologram can be considered to be thin, if the thickness is small compared to the average line spacing
- A thin hologram can be considered as a element which works in a thin layer
- The efficiencies of thin holograms are reduced due to higher orders, in best case for a amplitude modulation: 0.0625 phase hologram: 0.339
- Thick holograms are working in the volume and are based on the classical Bragg condition of interference
- Thick holograms typically have more problems with 1. finite absorption/transmission 2. dispersive behavior of the material
- The modelling of thick holograms with the volume effects needs for more complicated wave optical coupled mode theory
- For thick holograms, the efficiency depends more complicated on thickness, refractive/reflective, angle geometry,...
Thin vs Thick Holograms

- The parameter $Q$ allows for an estimation if a hologram is thick or thin more quantitatively

$Q = \frac{2\pi \lambda t}{n \Lambda^2}$

$t$: thickness of the hologram with refractive index $n$

$\Lambda$: averaged period of the grating

- If the maximum modulation $\Phi$ is considered as a function of $Q$, the following separation is obtained

![Graph of $\Phi$ vs $Q$ with Raman Nath thin grating, Bragg volume grating, and transition range]
### Diffraction efficiency of holograms

<table>
<thead>
<tr>
<th>Type of hologram</th>
<th>Theoretical</th>
<th>Experimental</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thin Holograms</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Absorption hologram</td>
<td>6.25 %</td>
<td>4 %</td>
</tr>
<tr>
<td>Phase hologram</td>
<td>33.9 %</td>
<td>30 %</td>
</tr>
<tr>
<td>Transmission (Bragg)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Absorption hologram</td>
<td>3.7 %</td>
<td>3.7 %</td>
</tr>
<tr>
<td>Phase hologram</td>
<td>100 %</td>
<td>90 %</td>
</tr>
<tr>
<td>Reflection (Bragg)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Absorption hologram</td>
<td>7.2 %</td>
<td>3.8 %</td>
</tr>
<tr>
<td>Phase hologram</td>
<td>100 %</td>
<td>95 %</td>
</tr>
</tbody>
</table>

Ref: R. Kowarschik
In-Line Holography

- In-line setup (linear, on axis, coaxial):
  - separation of diffraction orders critical
  - separation of orders digital
  - reduction of usable pixel numbers for reconstruction advantages
  - corresponds to Gabors original approach

Ref.: M. Kim
Holographic Off-axis Fresnel Setup

- Off-axis Fresnel holography
  - object at finite distance
  - reference wave plane
  - advantage:
    - easy separation of diffraction orders
  - relative inclination angle creates a carrier frequency

Ref.: M. Kim
Fourier Holography

- Fourier holography:
  - Fourier lens in 2f-configuration
  - use of a point source in the object plane as reference
  - hologram in image plane

Ref.: M. Kim
Image Plane Holography

- Imaging holography
  - hologram in image plane of a lens
  - reference wave directly overlayed
  - magnification can be used for scaling

Ref.: M. Kim
### Holographic Materials

- **Recording materials**

<table>
<thead>
<tr>
<th>Material</th>
<th>Modulation</th>
<th>Sensitivity (J/cm²)</th>
<th>Resolution (line pairs/mm)</th>
<th>Thickness (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photographic emulsion</td>
<td>Absorption or phase</td>
<td>( \sim 5 \times 10^{-5} )</td>
<td>( \sim 5000 )</td>
<td>(&lt;17 )</td>
</tr>
<tr>
<td>Dichromated gelatin</td>
<td>Phase</td>
<td>( \sim 7 \times 10^{-2} )</td>
<td>( &gt;3000 )</td>
<td>12</td>
</tr>
<tr>
<td>Photoresist</td>
<td>Phase</td>
<td>( \sim 1 \times 10^{-2} )</td>
<td>( \sim 1000 )</td>
<td>( &gt;1 )</td>
</tr>
<tr>
<td>Photopolymer</td>
<td>Phase</td>
<td>( \sim 1 \times 10^{-2} )</td>
<td>3000</td>
<td>3–150</td>
</tr>
<tr>
<td>Photoplastic</td>
<td>Phase</td>
<td>( \sim 5 \times 10^{-5} )</td>
<td>( &gt;4100 )</td>
<td>1–3</td>
</tr>
<tr>
<td>Photochromic</td>
<td>Absorption</td>
<td>( \sim 2 )</td>
<td>( &gt;2000 )</td>
<td>100–1000</td>
</tr>
<tr>
<td>Photorefractive</td>
<td>Phase</td>
<td>( \sim 3 )</td>
<td>( &gt;1000 )</td>
<td>5000</td>
</tr>
</tbody>
</table>

Ref: R. Kowarschik
Every real material for recording has some properties considering the transfer of signals.

This response function can be described by a modulation transfer function.

For a good quality of the imaging a linear response is necessary, which is typically achieved for medium sizes of the amplitude.

If the spatial frequencies are changing in the volume, the efficiency also changes with the position inside the hologram, which causes a limited spatial resolution.

Ref: P. Hariharan
Problems in Real Holography

- Aberrations due to non-perfect reproduced illumination beam
- Anamorphic effects due to strongly inclined angle geometry
- Non-paraxial real conditions in case of computer generated holograms
- Broadening due to a finite source size
- Broadening due to a finite bandwidth of the light of recording or reconstruction
- False light due to non-perfect suppression of straylight and higher diffraction orders
- Reduced contrast due to partial coherence
- Perturbation due to speckle or other noise origins
- Non-uniform brightness due to spatial varying efficiency of the hologram
- Blurring due to non-perfect mechanical stability during the exposure time (averaging)
- The finite size of the hologram area limits the spatial resolution of the image formation
Aberrations in Holographic Images

- Reconstruction of a hologram image by a modified non-ideal reading beam: geometrical aberrations, degradations and changes in the image

- Modified position of the reading beam:
  - change in image position
  - change in image orientation
  - spherical aberration

- Modified wavelength:
  - change in image z-location
  - changes in magnification
  - chromatical aberrations
Colored Holography

- Recording of three RGB colored single holograms by incoherent superposition
- The reconstruction is colored too
- Some problems in reality are cross talk and mixing effects
Fourier Holography Example

- Fourier off-axis hologram example

object  |  hologram with carrier  |  reconstruction with twin image

DH  |  |  DH  DH
Reconstrution at Different Angles

- Different viewing angles possible due to coded 3D information

- Rainbow hologram with color effects
Rough Surface Hologram

- Hologram of a smooth / rough surface
- Rough surface:
  - aperture completely filled
  - broadening of diffraction orders
  - diffraction orders overlap

Ref.: H. Naumann
Digital Holography

- **Main idea:**
  1. recording of the hologram not in a film medium, but digital with CCD (2D), reconstruction by pure calculation of wave propagation
  2. computation of the hologram by digital means (CGH = computer generated hologram)

- **Properties:**
  - possible, because sensors have nowadays better resolution
  - calculation possible due to larger computer power
  - real time processing can be achieved, impossible in conventional holography
  - simple image processing possible
  - phase unwrapping is in any case necessary
  - no problems with reconstruction stability
  - short exposure times, label-free high sensitive bio-medical applications
  - more flexible reconstruction: aberration compensation, $\lambda$ shift
  - CCD pixel size limits the lateral resolution

- **Applications:**
  - phase microscopy
  - deformation/vibration analysis
  - high resolution microscopy
  - testing of optical components by CGH
Digital Holography

- On-axis example
Digital Holography

- Off-axis hologram
Digital Holography

- Processing an image
Digital Holography

- 4 phase shifting hologram
Asphere Test with CGH

without CGH:

→ to much interference fringes
→ analysis impossible

with CGH:

→ flat wave-front
→ simple analysis

Ref: F. Burmeister
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, Reference marks (fiducials) necessary for proper positioning
- Expensive but very accurate method
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
Holographic Interferometry

- Disadvantages of classical interferometry:
  - Reference wave: only simple and reproducible wavefronts
  - Object wave and reference wave are required simultaneously
  - Only relatively small objects can be measured
  - Not applicable for rough surfaces

- Holographic interferometry can overcome these shortcomings

- Holographic interferometry:
  at least one of the two waves to interfere is created by a holographic reconstruction

Ref: R. Kowarschik
Holographic Interferometry

- Technical options:
  1. double exposure
  2. frozen reference wave, real time visibility of interferogram is possible

- The hologram saves a wanted reference wavefront, a comparison is possible at a different time of the change-measurement

- Processing steps:
  - recording the hologram of the reference state of the tested object
  - processing and replacement of the hologram
  - reconstruction
  - superposition of the virtual image with the real (changing) object wave

- Neighboured fringes correspond to an OPD of $\lambda$ between object point and observation point

- Applications:
  1. non-destructive testing
  2. measuring deformation
  3. perturbed propagation in scattering media

Ref: R. Kowarschik
Classical and Holographic Interferometry

- **Comparison of both methods**

<table>
<thead>
<tr>
<th>classical interferometry</th>
<th>holographic interferometry</th>
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<tbody>
<tr>
<td>comparison of two different objects</td>
<td>comparison of the same object in two different states</td>
</tr>
<tr>
<td>simple objects with smooth surfaces (lenses,...)</td>
<td>arbitrary objects, also rough surfaces</td>
</tr>
<tr>
<td>spatial separation</td>
<td>temporal separation</td>
</tr>
<tr>
<td>simple references (plane, spherical wave)</td>
<td>complex references</td>
</tr>
<tr>
<td>simple microstructure</td>
<td>constant microstructure</td>
</tr>
<tr>
<td>coherent light source</td>
<td>coherent light source</td>
</tr>
<tr>
<td>simple detector</td>
<td>high resolution sensor materials</td>
</tr>
</tbody>
</table>

Ref: W. Osten
Holographic Interferometry

- Principle:
  - recording of two holograms by different states of the object
  - difference of both pattern corresponds to an interference of the two changed waves
  - phase is unwrapped

Ref: W. Osten
Holographic Interferometry

- Shape measurement
  Classical setup

Ref: R. Kowarschik
Holographic Interferometry

- Shape measurement
  modified setup

Ref: R. Kowarschik
Holographic Interferometry

- Recording

Ref: R. Kowarschik
Holographic Interferometry

- Reconstruction

Object

Hologram

Shift of source point between illuminations

Ref: R. Kowarschik
Holographic Interferometry

- Geometry of shape measurement

![Diagram of holographic interferometry](image)

- Calculation

$$
N(P) = \frac{n}{\lambda} \left\{ \tilde{d}(P)(\tilde{e}_B(P,H) + \tilde{e}_Q(P,Q)) + \tilde{q}\tilde{e}_Q(P,H) + \tilde{r}\tilde{e}_R(R,H) + \tilde{q}(\tilde{e}_B(P,H) - \tilde{e}_R(R,H)) \right. \\
\left. + \left( \frac{\Delta\lambda}{\lambda} + \frac{\Delta n}{n} \right)(r_Q(P,Q) + r_B(P,H) - r_R(R,H)) \right\}
$$

Ref: R. Kowarschik
- Geometrical evaluation of the changes

Ref: R. Kowarschik
Holographic Interferogram Evaluation

- Variation of observation directions of a hologram
- Fringes move over the surface (basis of quantitative evaluation)
- Static evaluation:
  - different fringe pattern with regard to different observation points are taken as discrete states
  - 0th order has to be known
  - 3 orthogonally arranged holograms or 3 incoherent double exposure holograms
- Dynamic evaluation:
  - number and direction of moving fringes with regard to the interesting object point are taken as a basis
  - sequential observation of the object from at least 4 different points of the hologram
  - determination of the differences of interference fringes
  - number of observations directions extendable calculus of observation with computer

Ref: R. Kowarschik
Holographic Interferometry

- Sensitivity of the deformation/motion detection depends on the angles between reference and object wave
- Deformation changes behaves different for
  - in-plane changes
  - out of plane changes
Holographic Interferometry

- Example: deformed tennis ball with speckle

Ref: R. Kowarschik
Comparison

Fringe projection: shape measurement

Holographic interferometry: Measurement of deformation

Ref: W. Osten
Double Exposure Holography

- Double exposure technique
- Interference between recorded object wave fields

Process of method:
- hologram of the reference state of the object
- hologram of the changed object
- processing and non-critical replacement of the hologram
- reconstruction of both object wave fields

Ref: R. Kowarschik
Double Exposure Holography

- Double exposure technique: cylinder filled with hot water

Ref: R. Kowarschik
Holography

- Vibration analysis

Ref: R. Kowarschik
Vibration Analysis

- Holographic detection of vibrations of a driving car

Ref: W. Osten
Setup for double exposure technique

Sh: Shutter; PBS: polarizing beam splitter; MO: Micro-objectiv; M1, M2, M3: Mirrors; PRC: BGO Crystal; P: Polarisators; Wo: Wollaston-Prism; L1, L2, L5: Lenses; L3 – L4: Telescope.

Ref: R. Kowarschik
Double Exposure Holography

- Comparison: double exposure / real time

Ref: R. Kowarschik
Applications Fields of Holography

- Analysis of stress and strain
- 3D measurement of contours
- Nondestructive detection of defects

Ref: W. Osten
Defect Detection

- Shape and material defects at an aircraft

Ref: W. Osten