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Contents

1. Fourier imaging
2. Coherence
3. Phase imaging
4. Imaging in Zemax
Definitions of Fourier Optics

- Phase space with spatial coordinate $x$ and
  1. angle $\theta$
  2. spatial frequency $\nu$ in mm$^{-1}$
  3. transverse wavenumber $k_x$

$$\theta_x = \lambda \cdot \nu_x = \frac{k_x}{k_0}$$

$$k = 2\pi \nu$$

- Fourier spectrum $A(\nu_x, \nu_y) = \hat{F}[E(x, y)]$

  corresponds to a plane wave expansion

$$A(k_x, k_y, z) = \int \int E(x, y, z) e^{-i(xk_x + yk_y)} \, dx \, dy$$

- Diffraction at a grating with period $g$:
  deviation angle of first diffraction order varies linear with $\nu = 1/g$

$$\sin \theta = \lambda \cdot \frac{1}{g} = \lambda \cdot \nu$$
Resolution of Fourier Components

Ref: D.Aronstein / J. Bentley
Arbitrary object expanded into a spatial frequency spectrum by Fourier transform

- Every frequency component is considered separately
- To resolve a spatial detail, at least two orders must be supported by the system

\[ g \cdot \sin \theta = m \cdot \lambda \]
\[ g = \frac{\lambda}{\sin \theta} = \frac{\lambda}{NA} \]

Ref: M. Kempe
Number of Supported Orders

- A structure of the object is resolved, if the first diffraction order is propagated through the optical imaging system.

- The fidelity of the image increases with the number of propagated diffracted orders.
Abbe Theorie of the Microscopic Resolution

- Diffraction of the illumination wave at the object structure
- Occurrence of the diffraction orders in the pupil
- Image generation by constructive interference of the supported orders
- Object details with high spatial frequency are blocked by the system aperture and can not be resolved

Ref: W. Singer
Imaging of a crossed grating object
Spatial frequency filtering by a slit:

- Case 1:
  - pupil open
  - Cross grating imaged

- Case 2:
  - truncation of the pupil by a split
  - only one direction of the grating is resolved
Fourier Optics – Point Spread Function

- Optical system with magnification $m$
  Pupil function $P$,
  Pupil coordinates $x_p, y_p$

  $$g_{psf}(x, y, x', y') = N \cdot \iint P(x_p, y_p) \cdot e^{\frac{ik}{z} [x' (x' - mx) + y' (y' - my)]} \, dx_p \, dy_p$$

- PSF is Fourier transform of the pupil function (scaled coordinates)

  $$g_{psf}(x, y) = N \cdot \hat{F}[P(x_p, y_p)]$$

object plane
source point

image plane
point
image distribution
Fourier Theory of Incoherent Image Formation

- Transfer of an extended object distribution \(I(x,y)\)
- In the case of shift invariance (isoplanasy): incoherent convolution
- Intensities are additive

\[
I_{inc}(x', y') = \int\int_{-\infty}^{\infty} g_{psf}(x', x, y', y)^2 \cdot I(x, y) \, dx\, dy
\]

\[
I_{inc}(x', y') = \int\int_{-\infty}^{\infty} g_{psf}(x'-x, y'-y)^2 \cdot I(x, y) \, dx\, dy
\]

\[
I_{image}(x', y') = I_{psf}(x, y) * I_{obj}(x, y)
\]
Fourier Theory of Incoherent Image Formation

- **Object intensity**: \( I(x, y) \)
- **Squared PSF, intensity-response**: \( I_{psf}(x', y') \)
- **Convolution**
- **Optical transfer function**: \( H_{OTF}(v_x, v_y) \)
- **Fourier transform**
- **Result**
- **Image intensity**: \( I'(x', y') \)
- **Image intensity spectrum**: \( I'(v_x, v_y) \)
Fourier Theory of Coherent Image Formation

- Transfer of an extended object distribution \( I(x,y) \)
- In the case of shift invariance (isoplanasie): coherent convolution of fields
- Complex fields are additive

\[
E(x', y') = \int g_{\text{psf}}(x, y, x', y') \cdot E(x, y) \, dx \, dy
\]

\[
E(x', y') = \int g_{\text{psf}}(x - x', y - y') \cdot E(x, y) \, dx \, dy
\]

\[
E(x', y') = g_{\text{psf}}(x, y) * E(x, y)
\]
Comparison Coherent – Incoherent Image Formation

object

incoherent
bars resolved
bars not resolved

coherent
bars resolved
bars not resolved
Incoherent Image Formation in Frequency Space

- Incoherent illumination:
  No correlation between neighbouring object points
  Superposition of intensity in the image

\[ I_{inc}(x', y') = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \left| g_{psf}(x', x, y', y) \right|^2 \cdot I(x, y) dx \, dy \]

- In the case of shift invariance (isoplanasie):
  Incoherent imaging with convolution

\[ I_{inc}(x', y') = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \left| g_{psf}(x'-x, y'-y) \right|^2 \cdot I(x, y) dx \, dy \]

\[ I_{image}(x', y') = I_{psf}(x, y) \ast I_{obj}(x, y) \]

- In frequency space:
  Product of spectra, linear transfer theory
  The spectrum of the psf works as low pass filter onto the object spectrum
  Optical transfer function

\[ H_{otf}(v_x, v_y) = FT\left[I_{PSF}(x, y)\right] \]

\[ I_{image}(v_x, v_y) = H_{otf}(v_x, v_y) \cdot I_{obj}(v_x, v_y) \]
Complete description of an optical system:

1. Light source
2. Illumination system, amplitude response $h_{ill}$
3. Transmission object
4. Observation / imaging system with amplitude response $h_{obs}$
Coherence Parameter

- Finite size of source: aperture cone with angle $u_{ill}$
- Observation system: aperture angle $u_{obs}$

- Definition of coherence parameter $\sigma$:
  Ratio of numerical apertures

  $\sigma = \frac{\sin u_{ill}}{\sin u_{obs}}$

- Limiting cases:
  coherent $\sigma = 0$
  $u_{ill} << u_{obs}$

  incoherent $\sigma = 1$
  $u_{ill} >> u_{obs}$
Possible options in Zemax:

- Convolution of image with Psf
  1. geometrical
  2. with diffraction
- Geometrical raytrace analysis
  1. simple geometrical shapes (IMA-files)
  2. bitmaps
- Diffraction imaging:
  1. partial coherent
  2. extended with variable PSF
- Structure of options in Zemax not clear
- Redundance
- Field definition and size scaling not good
- Numerical conditions and algorithms partially not stable
Field size definitions

- Total field size in data (angle or length)
- Selected field index
- Relative size of structure in the total field
- Shown part of the field

- Not completely consistent in the different imaging tools
General Image Simulation

- Field height: size of object in the specific coordinates of the system
  - zero padding included (not: size = diameter)
  - image size shown is product of pixel number x pixel size
  - can be full field or centre of local extracted part of the field
- PSF-X/Y points: number of field points to incorporate the changes of the PSF, interpolation between this coarse grid
- Object: bitmap
- PSF: geometrical or diffraction
Geometrical imaging by raytrace

- Binary IMA-files with geometrical shapes
- Choice of:
  - field size
  - image size,
  - wavelengths
  - number of rays
- Interpolation possible
Geometrical imaging by raytrace of bitmaps

- Extension of 1st option: can be calculated at any surface
- If full field is used, this corresponds to a footprint with all rays
- Example: light distribution in pupil, at last surface, in image
Different types of partial coherent model algorithms possible
Only IMA-Files can be used as objects
$\alpha$ describes the coherence factor (relative pupil filling)
Control and algorithms not clear, not stable
Extended Diffraction

- Classical convolution of psf with pixels of IMA-File
- Coherent and incoherent model possible
- PSF may vary over field position
Geometric Raytrace

Object

7x7 pixel IMA file

10,000 raytraces
From random position inside object pixel
To random position in entrance pupil

Image

Spot diagram

Ref.: M. Eßlinger
Geometric Raytrace

1 ray per pixel

10 rays per pixel

100 rays per pixel

1000 rays per pixel

Ref.: M. Eßlinger
Imaging Objects

- **IMA (Image file)**
  - Illumination brightness in each point of the object
  - Zemax provides basic shapes like the letter „F“
  - ASCII format with 10 different grey values or binary with 256 grey values

- **BIM (binary image)**
  - like IMA, but 64bit (double precision) float values

- **ZBF (Zemax beam file)**
  - for sophisticated illumination optics
  - many features only available in Premium Version of Zemax

- **BMP (bmp, jpg or png)**
  - 3 x 8 bit RGB values (raytrace with FdC: 656 nm, 587 nm and 486 nm)
  - for greyscale detector: raytrace with FdC, averaging on detector plane
## Imaging: Summary

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### Advantages and Disadvantages of Geometric Raytracing

+ Easy to understand
+ Field dependent errors are considered automatically
- Does not include Diffraction Limit
- Requires large number of rays (slow)
- Coherent imaging is difficult (not possible with Zemax)