Solution of Exercises
Lecture Optical design with Zemax for PhD – Part 5

5.1 Transverse aberration curve

Establish a system with an ideal lens of focal length \( f = 100 \text{ mm} \), a wavelength of 600 nm and a collimated input bundle of diameter 10 mm.

a) Define the slider option with the image distance as a variable. Open the transverse aberration chart with a fixed scale of 100 \( \mu \text{m} \). What happens with the aberration curve, if the slider is moved?

b) Now introduce a thin glass plate in front of the perfect lens and define one side as a Zernike surface with coma as type \( (c8) \) of one wavelength. What is now the result for the moving slider?

Explain the result, if \( c7 \) is taken instead of \( c8 \).

c) If now spherical aberration is introduced by the plate in selecting \( c9 \), what is seen for the defocus?

Open also a spot diagram with fixed scale. Determine the best image plane for an overall small spot diameter?

Solution:

Setup of the initial system:

a) The slider option is used in the following setting:
As a result, the transverse aberration curve is tilted corresponding to the interpretation of the transverse aberrations in the case of defocussing.

b) The system looks as follows:

For a defocussing by the slider,

a strong parabolic shape due to the coma in the meridional plane is seen, which is tilted by the defocus.
If c7 is chosen the orientation of the coma is rotated and the parabola switches from the meridional to the sagittal plane.

c) For spherical aberration a cubic curve is superposed on the linear change. If the scale of the aberration curve is fixed to 300 $\mu$m, the best image plane is estimated to be at 101.44 mm. For this value, the residual zonal deviation has approximately the same size at the edge error.
5.2 Strehl ratio and geometrical vs Psf spot size

A single lens made of K5 with focal length \( f = 25 \) mm and thickness \( d = 5 \) mm is illuminated by a diverging beam with numerical aperture \( NA = 0.1 \). After the lens the light should be collimated. If the collimated beam is refocussed without further aberrations, the point spread function is not diffraction limited.

a) Calculate the accurate Strehl ratio, the estimated Strehl ratio and the geometrical and diffraction encircled energy inside the ideal Airy diameter.

b) If now the numerical aperture is reduced, the Marechal estimation becomes better. Calculate the largest \( NA \), for which the relative error is smaller than 2%. What amount for the geometrical and diffraction encircled energy inside the Airy diameter is obtained here?

c) Show the Strehl ratio as a function of the numerical aperture as a universal plot. What is the maximum value for getting a diffraction limited correction with \( D_S > 0.8 \)?

Solution:

a)

System data and layout:

If the cardinal points of the lens are calculated, the unknown first distance is obtained paraxially as \( t_1 = 25 - 3.280 = 21.72 \) mm

If the lens is reverted in its orientation and the distance is optimized over the complete pupil, the optimal distance seems to be 21.88 mm.
b) If the numerical aperture is changed, the following steps are performed:

1. Reduce NA
2. Determine the Airy diameter out of the spot diagram window
3. Set the aperture in the image plane exactly to the Airy value
4. Calculate the estimated Strehl ratio from the Zernike window
5. Calculate the accurate Strehl ratio from the Huygens PSF window with appropriate sampling
6. Calculate the geometrical encircled energy by the footprint diagram (with option: delete vignetting)
7. Calculate the diffraction encircled energy by the text output of the EE window.

Then the following table is obtained:

<table>
<thead>
<tr>
<th>NA</th>
<th>Strehl exact</th>
<th>Strehl estimated</th>
<th>relative error</th>
<th>Airy radius</th>
<th>geometrical EE inside Airy</th>
<th>diffraction EE inside Airy</th>
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</thead>
<tbody>
<tr>
<td>0.1</td>
<td>0.019</td>
<td>0</td>
<td>0</td>
<td>0.003299</td>
<td>0.0389</td>
<td>0.0394</td>
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<td>0</td>
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<td>0.0198</td>
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<td>1.0</td>
<td>0.7281</td>
</tr>
</tbody>
</table>

The relative error of the estimated Strehl ratio is smaller than 2% for NA < 0.051. Here the geometrical encircled energy is 45%, the diffraction calculated encircled energy 55%.
d) The universal plot is obtained with the following setting. Here it has to be noticed, that there is no refocussing included for the changing numerical aperture. If this is done manually, the Strehl ratio can be a little bit improved.

From the corresponding text window, we also get a limiting value of approximately $\text{NA} = 0.04$ for the diffraction limit.
5.3 Aplanatic lens

Consider a collimated incoming beam with wavelength 500 nm and diameter 10 mm. This bundle should be focussed by a perfect lens of focal length $f = 50 \text{ mm}$.

a) Place an aplanatic-concentric lens shortly behind the ideal lens with the material SF57. What is the resulting numerical aperture in the image space? Show at least two different methods to find the best image position.

b) Show that the spherical aberration of this setup is exactly zero for all orders.

c) Aplanatic means, that the linear coma vanishes and the imaging is free of coma for a small but finite field size. Show this property by using a small field of $2^\circ$ for the current system. What is the largest present aberration?

**Solution:**

The initial focussing lens is established as follows:

- A lens with thickness 1 mm is placed 1 mm behind the lens. The first surface is made aplanatic by a solve, the second surface is made concentric by choosing the solve 'marginal ray normal' to force the marginal ray to be concentric.
If a single ray trace is performed, we get the direction cosine of the marginal ray to be 0.1858. It can also be seen, that the marginal ray is concentric at the surface 5.

The best image position can be obtained by

1. Quick focus option
2. Solve at the last surface with marginal ray height 0
3. Pick up on the last (concentric) surface radius
4. Optimizing the last thickness as a variable with minimal spot size

b) If the Zernike polynomials are calculated, they are exactly zero for all orders.
c) If a field of 2° is introduced and the Zernike coefficients are calculated for the field point in the image and behind the 4th surface (the aplanatic), we get the following picture:

In the image, defocus (which is here in field the field curvature) and astigmatism are the dominating aberrations. Directly behind the aplanatic surface, only defocus has a considerable amount. This shows, that the concentric surface limits the system performance by astigmatism and field curvature. The change in the coma of the aplanatic surface is extremely small.