Computer exercise 3 – analysis of a system and methods for reducing the aberrations

In the former tasks, you have learnt to handle Synopsys and to set up optical systems. In this exercise, you will learn the analysis tools included in Synopsys. These allow you to evaluate the performance of your system. You will also test a few easy ways of reducing the aberrations of a system. All your system will have a focal length of 50 mm, the standard focal length of a camera lens (for full-format sensors).

Report: In order to report this exercise, you will need to save a lot of images and complement them with a little bit of text. I suggest you save the images by PrintScreen, then import them into e.g. Powerpoint, crop them and include comments. (Handling a lot of images with a small amount of text in Word can be quite frustrating, but you can try it if you feel very patient today.)

Part A: Analysis of a singlet lens

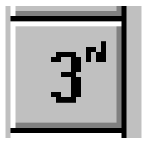
In this part, you will be introduced to the analysis features of Synopsys. You will also study the performance of a plano-convex lens with the flat side towards an object at infinity.

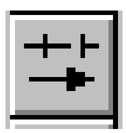
- Create a planoconvex lens, where the first surface is flat and the second has a radius of curvature of –25 mm. Make the glass BK7, and the thickness of the lens 3 mm. Place a solve on the distance from the lens to the last surface, to place the last surface at the image plane. Make the system units mm. Let the stop be at the first surface, and make the radius of the entrance pupil 10 mm.. Let the object remain at infinity, but make the object angle 5°.

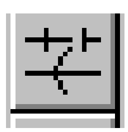
- We want the focal length of the lens to be 50 mm, so we should optimize the lens for this focal length. Go to the MOM dialog. (See task 1 if you have forgotten where to find it.) Choose the curvature of the second surface to be optimized.

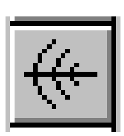
- Then, in the MOM dialog, we have to choose a merit function. Unlike last time, we will now construct our own merit function, which will tell the program exactly what parameters we want the lens optimized for. Click the button named “1:st, 3:rd, 5:th-Order Aberrations” to enter a new dialog. Here you can choose a number of parameters to optimize for. We will, however, only use one. Use the first row of the part named “First-Order aberrations”. If you click the arrow next to “Aberrations”, you get a number of parameters to choose from. Pick the focal length, FOCL. Give it a target value of 50 mm, and let the weight remain 1. (The weight tells how important a certain parameter is in the optimization. If you optimize for several parameters, you can give them different weights to tell the program which is the most important.) Make sure you click the square named “use” to activate the parameter. Then return to MOM.

- Click “Optimize now” to optimize the lens. Check the lens specifications. The focal length should now be 50 mm. Since the principal plane is at the surface, the image distance will be 50 mm too. As you can see in the PAD window, there is an awful lot of spherical aberration in this lens – the real marginal ray crosses the optical axis a long way from the paraxial focus. In the diagrams below the drawing of the system, you can see diagrams of some of the ray aberrations of the lens. Their shape is typical for spherical aberration. Save the image of the PAD window to your report file. Remember to save the lens file, e.g. as YourName3A.rls.

- If you press the  button on the sidebar, an aberration analysis will appear in the command window. Here you can find the size of all the aberration coefficients. As you can see, the spherical aberration and coma are huge, while the other aberrations are a bit smaller. Copy this information into the report. (You first have to press the “allow text select” button in the main window.)

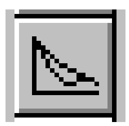
- By clicking the  button on the sidebar, you get ray diagrams (diagrams of the transverse aberration). They tell how far from the paraxial image point the rays will actually end up. Since this depends on where the ray passed the aperture of the lens, the distance is shown as a function of the pupil coordinate (X-coordinate for the sagittal fan and Y-coordinate for the tangential fan, since the object height is in the Y-direction.) The sagittal fan is always symmetric, so only half of it is shown. Since the diagrams are different for different image points, each diagram is plotted for some different relative field positions. When the relative field is 1, the image point is at the edge of the image. When it is 0, the image point is on the optical axis. For this position, the sagittal and tangential fans coincide, so only one of them is shown. Include the image of the ray diagrams in your report.

- By clicking the  button, you get to see the wavefront aberrations (the difference in optical path) instead. Here we see the distinct X^4 behavior of spherical aberration for the sagittal fan, while the tangential fan shows a mixture of the Y^4 of spherical aberration and the Y^3 of coma. Include this image in your report.

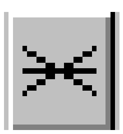
- If you click the  button, you find several different options to choose from. The first one is “Show the shape of the exiting wavefront”. This description is not entirely true, since you will really get the shape of the exiting wavefront *aberrations*, i.e., the difference between the exiting wavefront and a spherical wavefront converging towards the image plane. The color number is P, which means primary colour (in this case the green one). This is good. The fractional Y-field should be a number between 0 and 1, where 0 means the wavefront converges towards the optical axis, and 1 that it converges towards the edge of the image. The fractional X-field should be 0, since we have no skew object defined in the X direction.

You can choose whether to see the wavefront as a surface or a contour map. In this case the aberrations are large and the surface difficult to display (test it!) so I suggest using the contour map. Make contour maps for Y-field 0 and 1. Include them in the report file. Comment on the difference between them!

- Continuing in the same menu, the second next option is “Diffraction pattern intensity distribution”. As before, the colour is the primary colour (P), the fractional Y-field should range between 0 and 1, and the fractional X-field should be 0. With this lens, the program has some problems: the aberrations are too big, and the output not trustworthy (check the error messages). Have a look at the graphs, but don’t include them in your report file (there’s no point, since they are not accurate).

- By clicking the  button, you can get the MTF curve of the system. The colour should be P, the X-field should be 0, and the Y-field should vary between 0 and 1. Then click the MTF button to get the curve. Since the resolution varies with the position in the image field, the MTF curves for different image positions will look different.

  Find the MTF curve for a fractional Y-field of 0 and 1. Is the system diffraction limited? Motivate your answer.

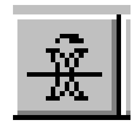
- The  button again provides a number of opportunities. The first one is the spot diagram, SPT. The program tracks a number of rays from the same object point, and marks the places where they end up in the image plane. The colour should be P and the fractional X-field 0. For a fractional Y-field of 0 and 1, find the spot diagrams and include them in your report.

- The MTS option gives you through-focus spot diagrams, i.e., several spot diagrams for different positions along the optical axis. This way you can see how the focus changes as we go through it, and you can also see how different colors focus at different places (chromatic aberration).

- With the MTG option, you can make through-focus MTF curves.

Part B: Turning the lens affects the performance

In this part, you will do the same kind of analysis for the same lens, but turned the other way around.

- Now turn your lens around! There is a quick way to do so: use the  button in the main window. You can also do it by hand in the Surface Data spreadsheet. Note that although the focal length is the same, the image distance has changed since the front principal plane is no longer at the lens surface. Include the PAD window in your report.

- Check the third-order aberrations, and include them in your report. Compare them to those of task A. Have they increased or decreased? Would you expect this system to perform better or worse than the last one?

Part C: Splitting the lens power

- Try splitting the power of your lens on two plano-convex lenses. Construct a system of two identical lenses, each with a curved surface of radius 50 mm towards the objec and a flat surface towards the image plane. Let their thicknesses be 3 mm and the glass BK7. Use pick-ups to make the two lenses identical. Let the object and aperture data be as in 3A and 3B. Make the distance between the lenses 0.

- Optimize the system to give it a focal length of 50 mm. Check the lens specifications to see that you really get this focal length. Include the PAD window in your report.

- Check the third-order aberrations, and include them in your report. Compare them to those of task A. Have they increased or decreased? Would you expect this system to perform better or worse than the last one?

- Now do the same kind of analysis as in task A, and include the same kinds of graphs in your report. For each set of graphs, compare the performance of the two systems: does this one perform better, worse or approximately the same as the one in task 3A? Include those comments in the report.

- Why do the chromatic effects show more clearly in the graphs of part C, although the chromatic aberration is the same as in A?

Part D: Compensating for chromatic aberrations

So far, we have only investigated singlet lenses, normally planoconvex or equiconvex. These are very crude, and in imaging optical system they can only be used for “easy” tasks. Often, doublets are used instead. They are very good for compensating for chromatic aberrations (see chapter 7 in “Optical design and construction” by Axner). But they can also be used to reduce other aberrations, e.g., the spherical aberration. We will construct and optimize such a lens, and then analyse its performance.

- Before you can optimize the lens, you need a starting point. (Otherwise the optimization might change your system beyond recognition and still not take away any aberrations.) Make a cemented doublet, i.e., one where the last surface of the first lens coincides with the first surface of the second lens. Then you need four surfaces: three for the doublet lens and one for the image plane. Let the first lens be made of BK7 and have radii r_{11}=25 mm and r_{12}=-25 mm, with thickness 5 mm. (Don’t use pick-up on the second surface – we don’t know if their curvatures will remain the same.) The second lens should be 2 mm thick, made of SF5 and its last surface should be flat. Then the lens consists of one posistive equiconvex lens, and one negative plano-concave lens. This is a good starting point, since most achromatic doublets look approximately like this.

- Include the aperture details: the aperture is at surface 1, and the entrance pupil radius is 10 mm. The object should be at infinity and the object angle 5°. Make the system unit mm. Use a solve to place the last surface at the paraxial image plane. Save the system - there is no way to undo the optimization if it goes wrong.

- In order to optimize the system, go to the MOM dialog. Pick the curvatures of all three surfaces to be optimized. Then go back to MOM.

- Now we need to construct a merit function. This time, use number 4 of the prepared merit functions. In this merit function, different parameters of the system are included with different weights, in a way that has been found to give good results. However, it doesn’t include one parameter important for our system: the focal length. We need to add more to the merit function. Go to “1:st, 3:rd, and 5:th order aberrations” and set the focal length to 50 mm with weight 1. Then go back to MOM. Now you see that both merit functions are in use.

- Optimize the system. Check the PAD window, the system specifications and the aberrations. The lens should still look approximately like an achromatic doublet, have a focal length of approximately 50 mm, and the aberrations (in particular the spherical aberration and the longitudinal chromatic aberration) should be a lot smaller than for the singlet lens. If those conditions are not fulfilled, you need to try another starting point or another optimization function.

- Now analyze this system as you have analyzed the singlet lenses before! Remember to include the PAD drawing in your report. Comment on the performance of the lens, compared to the singlet lenses. Is this lens diffraction limited?

For this lens, the Diffraction Pattern Intensity distribution is OK at least on the optical axis. Make it a surface, not a contour plot – it looks nicer this way. Also test the through-focus spot diagrams – they look quite nice, and you can see how the focus changes for different colours and for different image heights.