Computer exercise 2 – geometrical optics and the telescope

In this exercise, you will learn more of the tools included in Synopsys, including how to find system specifications such as focal length and F-number. You will see how the wavelength of light affects the focal length of a lens. You will also get to use Synopsys more independently, in setting up a simple telescope.

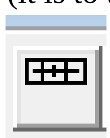
Part A: The thick lens

From the lens-makers formula, you can easily find the focal length of a thin lens. For a thick lens, the focal length will change. In this task, we will use Synopsys to find out how the focal length of the lens varies with the thickness of the lens. You will also learn how to include an object at a finite distance, and how to find the focal length of a system.

- Use the Surface Data spreadsheet to make a lens of radius of curvature r_1=30 mm and r_2=-30 mm. Place the stop at the lens (i.e., at the first surface), and make the radius of the entrance pupil 5 mm. Pick the glass BK7 for the lens, and let its thickness be 0. Put a solve on the distance between the lens and the image, to place the last surface at the image plane. Check exercise 1 if you have forgotten how to construct the lens.

- In the System Data dialog within the Surface Data spreadsheet, pick mm as lens unit. In the "Object wizard", choose the options "Finite object" and "Fixted size (YP0)". In the "Formatted input" area, make the object distance THO 75 mm and the object height YP0 10 mm. Close the dialog. (You might hear a warning beep if you change the Object distance before you change the Y-height. Just ignore this.)

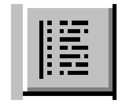
- If you open the PAD window, you will see a drawing of the system. Unfortunately, the object is not included (it is to the left of the image). Click the

  button on the PAD window menu, and set the "Starting Surface" of the "Y-Z Profile Drawing" to 0. Now you should see both the object and image planes. Print the PAD window. The lens will look quite weird – since its thickness is zero, and Synopsys still tries to draw the curved surfaces in the correct places, it will look like a negative lens in the drawing. It is still a positive lens, though, as you can see from the refraction of the rays.

- Save the lens as e.g. YourName2A.rle.

- What is the focal length of the lens? Find it theoretically, using the refractive index for wavelength 2. Write your calculations on the printed page.

- What is the focal length according to Synopsys? If you click the button on  the sidebar of the main program, a listing of the system properties will appear in the Command window. (The command window is the one that has always been there, but that we haven't used before.) You can also get this listing by writing SPEC directly in the Command window. One of the listed properties is the focal length (FOCL). Compare this value to your theoretical calculation. Write the result on the sheet of paper.

- What should the image distance be? Find it theoretically, and compare it to the image distance in Synopsys. The image distance (BACK) is one of the properties listed in the specification. Write the results on the paper.

- What is the magnification? Find it theoretically, and compare it to the magnification found by Synopsys. The magnification is listed further down in the specification, but you can also find it by dividing the image height (GIHT) by the object height (YPPO). Write the results on the paper.

- Now change the thickness of the lens to 1 mm, and use Synopsys to find the focal length, the image distance and the magnification. You can either list all the properties in the command window, or you can ask for a specific property by writing e.g. FOCL? or BACK? in the command window.

- Make a table where you write down the focal length, the image distance and the magnification for some different thicknesses: 0, 1, 3, 5, 10 and 20 mm. Write the table on the sheet of paper.

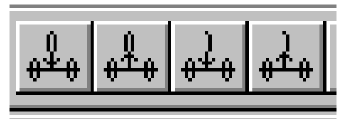
Report: Part A should be handed in as a single sheet of paper. On the paper should be the drawing of the system when the lens thickness is 0, together with the theoretical calculations of the focal length, image distance and magnification. There should also be comparisons to the same values found by Synopsys. Finally, there should be a table of the focal length, the image distance and the magnification (all found by Synopsys) for some different thicknesses: 0, 1, 3, 5, 10 and 20 mm.

In your table, you should find that the focal length gets longer when the thickness increases. But the image distance, which should increase when the focal length increases, instead gets shorter and shorter. Try to find an explanation for this! Write your thoughts down.

Don't forget to write your name and the exercise number 2A on the paper.

Part B: Refractive power of two lenses

In this part, you will investigate how the focal length of a system of two lenses changes when the distance between the two lenses is increased.



- Take the lens you produced in task 2A. Open the PAD window. In the toolbar of the main window, you can now find four buttons for inserting or removing extra lenses or surfaces in the system. Click on the first one, then click at the PAD window to the right of the lens. Now a new lens has been inserted after the first one. Since the program doesn't know what kind of lens you wanted, it just inserts two flat surfaces with a refractive index picked up from the first lens.

- Enter the Surface Data editor and make both lenses identical: r_1=30 mm, r_2=-30 mm, and thickness 1 mm. Since the solve that was placed on the last distance was removed when you inserted the lens, you need to insert a new one. Now the program should automatically place the last surface at the paraxial image plane.

- Make the distance between the two lenses 0. Make sure you can see both the object and the image planes, then print the PAD window. Save the lens file as YourName2B.rls.

- Make a table where you display how the focal length, the image distance and the magnification change as the lenses are moved further and further apart. Use the distances 0, 1, 3, 5, 10, 20 and 40 mm. Write the table on the printout from the PAD window. (Note that if you want to, you can change the thickness by moving the sliders in the Lens_Edit window.)

- What happens when the distance between the lenses is increased? If you have two positive lenses and want a system of as short focal length as possible, where should you place them relative each other? Write your conclusions on the paper, too.

Report: Part B should be handed in as a single sheet of paper. On the paper should be the drawing of the system when the distance between the lenses is 0. There should also be a table of the focal length, the image distance and the magnification (all found by Synopsys) for some different separations: 0, 1, 3, 5, 10, 20 and 40 mm. Write down your conclusions on the effect of the lens separation on the focal length of the system. Don't forget to write your name and the exercise number 2B on the paper.

Part C: Wavelength effects on the focal length

Since the refractive index depends on the wavelength, so does the focal length of a lens. You will investigate, for two different kinds of glass, how the focal power changes with the wavelength.

- Load the lens from task 2A again. Give it a thickness of 3 mm. The glass should be BK7, which is the most common crown glass.

- Enter the System Data dialog in the Surface Data spreadsheet. Change the number of defined wavelengths from 3 to 1, to get a system for monochromatic light. Make the first wavelength 400 nm (0.400 μm). Click "update wavelengths" for the changes to take effect.

- Make a table of the refractive index and the focal length as functions of the wavelength. Use 400 nm (purple), 450 nm (blue), 500 nm (green), 550 nm (green), 600 nm (red), 650 nm (red) and 700 nm (red).

- Change the glass of the lens to SF11 and do the same thing. This is a flint glass, which has both higher refractive index and higher dispersion. How does this show in the tables?

- Make four graphs, showing the refractive index and the focal length of both BK7 and SF11, as functions of the wavelength.

Report: The report should consist of the two tables of refractive index and focal power as a function of wavelength for BK7 and SF11, and the four graphs that result from them. The graphs should be neat and the axes properly named and scaled. Mark the papers with your name and the number 2C of the exercise.

Part D: The telescope

Reading: Please read section 5.7.7 in "Optics" by Hecht.

Task: Your task is to create two telescopes, one astronomical (two positive lenses) and one Galilean (one positive, one negative). The first should have an angular magnification of approximately –4, and the second approximately +4. All lenses should be plano-convex or plano-concave, with the curved surface turned towards the flat field (i.e., towards the object for the objective and towards the eye for the eye-piece). The aperture stop should be at the objective, which should have a focal length of around 90 mm and an aperture radius of 10 mm. The eye-piece should be smaller than the objective – this will limit the field of view.

Report: The report should contain a short description of how you constructed the telescopes, PAD drawings of the system and SPEC listings for the two systems. Remember to include your name and the number 2D of the exercise.

Useful advice on afocal systems

A telescope is an example of an afocal system, i.e., a system where both the object and the image is at infinity. How to place the object at infinity was described in exercise 1. To get the image at infinity, though, requires use of the 'afocal' option in Synopsys. In the System Data spreadsheet, which you reach via the Surface Data spreadsheet, there is a part called 'Other system options'. There you can change the option 'focal' to 'afocal.

However, this is not enough. This option also requires that you insert two extra surfaces after the last lens. Those two surfaces should be flat and in the same place. It is good to place them some distance from the last lens, since the plots of the system will include the rays until they hit this extra, double surface.

Tip

If you have the PAD window open, you also see the "Work-sheet lens-edit window". Here you can select a surface, and then change the properties of that surface (e.g. curvature or spacing) by using the sliders. Then you can see, in real-time, how the drawing in the PAD window changes, and let go of the slider when the system looks good.

What is good enough?

This is just a training session and there are no demands on optical quality. For this task, it is sufficient that the lens system could function as a telescope. A telescope has infinite system focal length, but in this case, that translates as a system focal length that is much longer than any of the lens focal lengths involved.