Cooke Triplet Optimization

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Cooke Triplet Intro

A Cooke Triplet is made of 3 lenses (two positive lenses, and one negative lens). The design was initially conceptualized in the late 1800s as an alternative to other lens systems present at the time. This system uses only 3 lenses, in comparison to the 6, 8, or more of those other systems. The lens parameters are known to be optimizable to reduce not only chromatic aberrations (properties of doublets) but also monochromatic aberrations (such as spherical aberration and field curvature), exploiting symmetry.

Project Scope

Our goal was to build and optimize a Cooke triplet in Zemax Optical Studio, performing analyses of the spot diagrams and ray fan plots to make design choices and considering tolerances of the various parameters to understand how those impacted our results. We wanted to find a way to begin at a very coarse starting point (knowing simply that we would use 3 lenses, at some distances apart on the optical axis) and do literature research and simulations to enhance our results.

Finding an Optimal Triplet

A Cooke Triplet has 6 surfaces, 3 airspaces, and 2 lens materials (suppose two positive lenses have the same material)--altogether 11 variables for us to use to correct for 7 Seidel aberrations (spherical aberration, aberration, coma, astigmatism, astigmatism, field curvature, distortion), as well as chromatic aberrations with lens materials being a combination of flint and crown. To find the optimal lens, we solve the optimization problem of minimizing spot size with the aforementioned 11 variables. However, lens material is a discrete variable, which does not fit into the generic optimization algorithms as other continuous variables. Therefore, we first use our understanding of optics to figure out what glasses for the two lenses are. (Although "glass substitution" process can be automated by Zemax, but it takes a long computational time and is not a process as insightful as we would like.)

Discrete variables: Glass Selection

We first recognized that a high difference in Abbe number (V) was necessary between the two materials (page 8 of the slide), in order to minimize chromatic aberrations (in accordance with the formula relating focal length to EFL and V). Additionally, to minimize the Petzval sum, we needed materials of high refractive indices. Crown and Flint were hence chosen (page 9). However, there are many different kinds of these glasses (for example, even within flint: barium light flint, special short flint, etc.). Based on our research, we found that for the positive lens, LaFN-21 (Lanthanum Flint) was optimal, and we selected 3 candidate glasses for the negative lens (page 11,13,14,15). In order to analyze the tradeoff between vignetting (the limiting of off-axis rays at the edges of the diagram) and image quality, we created spot diagrams and vignetting diagrams. We then chose a material which enabled relatively lower vignetting with moderate improvement in image quality: SF-15.

Continuous variables

Once we have nailed down the glass selection in the system, we could simply apply Zemax to find other optimal variable values with default objective function (called merit function in Zemax) to minimize spot size under columinated light that spans the entrance pupil. The merit function consists of the weighted difference between the system output and the targeted size of various metrics, such as axial differences of the ray intersection with the chief ray in the image plane from various field angles. Minimizing the merit function finds a design that gives overall minimum aberrations. We do this with our constraint of having the EFL=52mm. We then obtain the design shown on page 17 of the slide. Note that we did not resort to "global optimization" function in the Zemax which would include jumps to escape local minimums to explore global minimums. Due to its long computing time, and its inability in the process to offer optical insights as it is more of an optimization method problem rather than optical modeling problem, we used the relatively fast "Optimize" function in Zemax, and the initial condition does not matter too much for the final result.

Optimal Triplet Performance Analysis

To see how the optimal design perform optically, we plotted spot diagram (p18 of the slide), ray fan plot(p19), distortion level plot (p24). Since we did not cover "ray fan plot" in class and since they are not intuitive at first glance, we included pedagogical slides on p20 and p21 as a reference. The first thing to notice is that there is not much chromatic aberrations. As for other monochromatic aberrations, the system shows minimal aberration sagittally. Tangentially it has slight aberrations including but not limited to coma, spherical aberrations. A complete diagnosis of aberrations is beyond the scope of this project as detailed analysis of aberrations can be a project on its own. However, here we offer one insight in lens design. All aberrations interact. In slide page 27, we show that when we specifically add in weights on spherical aberration in the merit function, we could actually do worse overall. This is evident from the spot diagram that are more wide-spread from the center in the case with added spherical aberration weight. Therefore, we see that Zemax default merit function is constructed non-trivially (although quite simple to understand) such that it models the overall aberrations. If we specifically want to "over-correct" for one specific aberration, we might introduce other aberrations as a cost.

Finally, using the image simulation function in Zemax, we simulated the image the triplet would give us compared to an ideally imaged scene. The result in included in slide page 25 and 26. We see that there is perceivable distortion in the field when compared to the ideal image, and vignetting might affect our perception as well. However, if we only look at the triplet image, we could resolve almost as much as the ideal image without perceivable aberrations and distortions.

Practical concern: tolerance and sensitivity analysis

Tolerance analysis is preferred as we cannot manufacture lens system perfectly as we have designed. This analysis allows us to know the most sensitive parameters. The most often used parameters are tilt, decenter and curvature.

In our system we have three lenses. For each lens, we used surface tolerance including radius, thickness, decenter, tilt and irregularity, element tolerance including decenter and tilt, index tolerance including reflective index and abbe number. As the system is symmetric, we eliminate the y direction parameters. We used more tolerance parameters to model the interaction between lenses and and the total parameter added up to 42.

The tolerance process generates the parameter in a given range, in which we refer to a precision standard and use a Monte Carlo way to generate 20 iterations. We analyze the sensitivity and the whole performance of the system. First we have the sensitivity analysis. Results are shown in p36 of the slide. We see that the most sensitive parameters are the decenter and tilt, which means these have the biggest influence on the final performance. Then we did the accuracy analysis (p37 of the slide). We used the RMS wavefront error function. We can see that during the 20 iteration, more than 80% of the circumstances the error is larger than 3.46, so we consider the system error to be 3.46.

Reference

Cooke Triplet Review

https://www.willbell.com/tm/ChapterB.3.pdf

Aberration in Lens Design

http://www.montana.edu/jshaw/documents/10%20EELE582_S15_Ray_Aberrations.pdf

http://www.photonics.intec.ugent.be/education/IVPV/res_handbook/v1ch33.pdf

https://wp.optics.arizona.edu/jsasian/wp-content/uploads/sites/33/2016/03/Opti517-Optical-Quality-2014.pdf

Optimization and Zemax OpticStudio

http://ecee.colorado.edu/~ecen5616/WebMaterial/15%20Optimization%20and%20Tolerance.pdf

Operands can be found here on page 491:

https://neurophysics.ucsd.edu/Manuals/Zemax/ZemaxManual.pdf

Tolerance Analysis

https://my.zemax.com/en-US/Knowledge-Base/kb-article/?ka=KA-01675

https://my.zemax.com/en-US/Knowledge-Base/kb-article/?ka=KA-01417

https://wp.optics.arizona.edu/optomech/wp-content/uploads/sites/53/2016/10/521.Tutorial.Zemax-Tolerancing.Haynes.pdf

APPENDIX

RESULTED LENS DATA:

Surfaces : 7
Stop : 5
System Aperture : Entrance Pupil Diameter = 14.8571
Fast Semi-Diameters : On
Field Unpolarized :On
Convert thin film phase to ray equivalent : On
J/E Conversion Method : X Axis Reference
Glass Catalogs : SCHOTT
Ray Aiming : Off
Apodization : Uniform, factor = 0.00000E+00
Reference OPD :Exit Pupil
Paraxial Rays Setting : Ignore Coordinate Breaks
Method to Compute F/# : Tracing Rays
Method to Compute Huygens Integral : Auto
Print Coordinate Breaks : On
Multi-Threading :On
OPD Modulo 2 Pi : Off
Temperature (C) : 2.00000E+01
Pressure (ATM) : 1.00000E+00
Adjust Index Data To Environment : Off
Effective Focal Length : 52 (in air at system temperature and pressure)
Effective Focal Length : 52 (in image space)
Back Focal Length : 42.16237
Total Track : 63.3681
Image Space F/# : 3.5
Paraxial Working F/# : 3.5
Working F/# : 3.424868
Image Space NA : 0.1414213
Object Space NA : 7.428571e-10
Stop Radius : 5.953151
Paraxial Image Height : 21.64551
Paraxial Magnification : 0
Entrance Pupil Diameter : 14.85714
Entrance Pupil Position : 17.61922
Exit Pupil Diameter : 12.91092
Exit Pupil Position : -44.28473
Field Type : Angle in degrees
Maximum Radial Field : 22.6
Primary Wavelength [µm] : 0.55

Angular Magnification : 1.150742
Lens Units : Millimeters
Source Units : Watts
Analysis Units : Watts/cm^2
Afocal Mode Units : milliradians
MTF Units : cycles/millimeter
Include Calculated Data in Session File : On
Include Calculated Data in Session File : On