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Introduction

Lens design is an exciting and important field of optics. This field provides designs for a great diversity of lens and mirror systems needed in many other fields, such as consumer optics, microscope optics, telescope optics, lenses for optical lithography, and photographic optics. Lens and mirror systems are ubiquitous. The work of a lens designer is to provide the constructional data and fabrication tolerances of all the optical elements that a given lens system requires to perform the intended function. Currently many students and engineers are interested in lens design because the field by itself is of great interest, or because they have the need to analyze and design lens systems required in their engineering practice. An optical engineer should have at least some familiarity with how a lens system is designed so that he or she can effectively contribute to develop optical systems.

1.1 Aims of This Book

This book is an introduction to lens design, and has been written to provide an overview of topics that are indispensable to acquire the skill of lens design. Acquiring this skill, the skill of lens design, requires learning some theory, learning how to use lens design software, and gaining experience by designing actual lenses. This book will help the interested reader to understand the theory and methods used in lens design. The book does not have lengthy discussions but, rather, brief discussions to point out essential knowledge. A few references are given for further reading, where the reader can deepen his or her knowledge about a topic.

There are many excellent books about lens design, such as *Lens Design Fundamentals* by Rudolf Kingslake and Barry Johnson, and *Modern Lens Design* by Warren Smith. However, these and other comprehensive books might not be appropriate for an introduction to lens design, as part of their main focus is the design and survey of a variety of specific lenses. Instead, this introductory book intends to be brief and also to give an overview of topics that a current optical engineer needs to know about lens system design. A graduate student or an optical engineer who understands the content of this book and models, in a lens design program, the different lens systems discussed in it, would then have a solid foundation to practice the skill of lens design. Another aim of this book is to provide an efficient introduction to lens design to an interested student or optical engineer, so that he or she is well positioned to analyze, combine, debug, adjust, or design lens systems.

1.2 Topics Covered

Essential to lens design, and to optical engineering, is an understanding about how optical aberrations are corrected, balanced, or minimized. The reader should have some familiarity with first-order optics and with the theory of optical aberrations, as many discussions revolve about the choices made in the layout of a lens system and how to correct the aberrations. In this book, structural aberration coefficients are used to determine primary aberrations and to understand how to correct, balance, or minimize them. Chapter 2 provides a review of first-order optics and aberrations. Chapter 3 provides a brief discussion of aspheric surfaces. Chapter 4 provides a discussion of thin lenses and how aberrations are controlled in very simple lens systems. Chapter 5 provides a discussion about how ray tracing takes place, and some useful techniques. Chapter 6 provides a discussion about radiometric aspects of a lens system, which are important for a more comprehensive understanding of how lenses work. Chapter 7 discusses achromatic and athermal lenses. Chapter 8 provides a number of lens examples that use combinations of achromatic doublets. This chapter is insightful because it shows how lenses are combined. Chapter 9 discusses the tools used to determine image quality. Chapter 10 discusses how to perform a tolerancing analysis for providing tolerances to the constructional parameters of a lens system that will be manufactured. Chapter 11 comments on issues in using a lens design program. Chapter 12 discusses three classical lenses; the Petzval portrait objective, the Cooke triplet, and the double Gauss lens. Chapter 13 discusses issues that arise in combining lens systems; it also contributes to providing a more comprehensive view about lens systems. Chapter 14 discusses designing with off-the-shelf lenses. Chapter 15 discusses ghost images in a lens system. Chapter 16 discuses some basic mirror systems. Chapter 17 discusses miniature lenses. Chapter 18 provides basic concepts in zoom lens design. In addition to a glossary of terms, the book provides five Appendices, where several tables related to aberrations are provided, as well as a discussion of the sine condition. Thus, the book contents provide a shift in the way lens design is taught. In this introductory book there is more emphasis on providing a broader view of fundamentals and essential topics in lens design, rather than bringing attention to the detailed design of a survey of lenses. This shift responds to current needs in the optical industry, and modern approaches to learning. Yet, this book provides a solid introduction for those who would like to specialize in the art of lens design.

1.3 The Art of Lens Design

There are many types of lens systems, and their variety is increasing with advancements and the creation of new technological fields. Examples of lens types are projection lenses, telephoto lenses, convertible lenses, catadioptric lenses, zoom lenses, underwater lenses, lenses for aerial photography, anamorphic lenses, panoramic lenses, lenses for video and cinematography, lenses for scanning, relay lenses, periscope lenses, and lenses for endoscopes.

The process of lens design starts with understanding the application the intended lens is to be designed for. From understanding the application, the lens specifications list follows. This list of specifications is not always complete or correct. A lens designer must make efforts to verify that the specifications list is as complete and correct as possible. The lens specifications may involve first-order, packaging, image quality, environmental, and lens fabrication constraints and requirements. Once the specifications are understood, the lens designer may start a design from first principles, and by adding complexity to simple lenses. A first-order lens layout can help to visualize a given lens and determine, for example, lens size, element optical power, and type of lens configuration. From the first-order layout, considerations are made about how the aberrations could be corrected. Then a lens design program is used to model and optimize the lens system, and to find alternative lens solutions for comparison. A lens analysis is also made to determine tolerances that a lens manufacturer would need to make the lens elements. A lens design can also start from existing lenses in the patent literature. A lens designer should have effective communication with the opto-mechanical engineer and lens manufacturer to make sure that the designed lens can be mounted in a barrel, fabricated, and assembled. Lens drawings are then drafted. Some optical engineers may not actually design lenses, but would analyze, debug, adjust, and combine existing lens systems. A critical design review is often held to approve, or disapprove, a lens for fabrication. The overall process of lens design is also of exercising design creativity, and this in part is what makes lens design an exciting field.

Further Reading

Bentley, Julie L., Olson, Craig, Youngworth, Richard N. "In the era of global optimization, the understanding of aberrations remains the key to designing superior optical systems," Proceedings of SPIE 7849, Optical Design and Testing IV, 78490C (2010); doi: 10.1117/12.871720.

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2

Classical Imaging, First-Order Imaging, and Imaging Aberrations

This chapter provides a brief overview of essential imaging concepts used in lens design. Whether classical imaging, which is congruent with first-order optics, is required in a lens system, or any other type of imaging, depends on system application. Therefore, a clear understanding of what imaging is and of departures from such imaging, called aberrations, is essential for a lens design practice.

2.1 Classical Imaging

The main goal in lens design is the design of imaging lenses where images, particularly sharp, are formed. Then it is important to discuss the concept of an image. Depending on application, different imaging concepts can be devised. However, classical imaging, where the image is a scaled copy of the object, is often required for a lens system. The underlying mechanism for classical imaging is central projection. Object points are projected into image points on an image plane, by the line defined by an object point on the object plane and a central projection point pair as shown in Figure 2.1. The projection point pair is the center of perspective and in a lens system, which we assume to have axial symmetry, is represented by a nodal point in object space and its conjugate point, the nodal point in image space. The main attributes of a classical image are its location and its size. The Newtonian or Gaussian imaging equations shown in Table 2.1 permit calculating these attributes and represent central projection imaging.

Ideal imaging as defined by central projection is often a designing goal. For an object at infinity that subtends a semi-field of view, θ, the image height, $\bar{y}_i$, measured from the optical axis, is related to the focal length, f, by the mapping, $\bar{y}_i = f \cdot \tan(\theta)$. However, according to application, there are other

Table 2.1 *Imaging equations*

Newtonian equations	Gaussian equations
$\frac{z}{f} = -\frac{1}{m}$	$\frac{f'}{z'} + \frac{f}{z} = 1$
$\frac{z'}{f'} = -m$	$\frac{z}{f} = 1 - \frac{1}{m}$
$zz' = ff'$	$\frac{z'}{f'} = 1 - m$
The object and image distances z and z' are measured, respectively, from the front and rear focal points. f and f' are the front and rear focal lengths.	The object and image distances z and z' are measured, respectively, from the front and rear principal points. The transverse magnification is m.

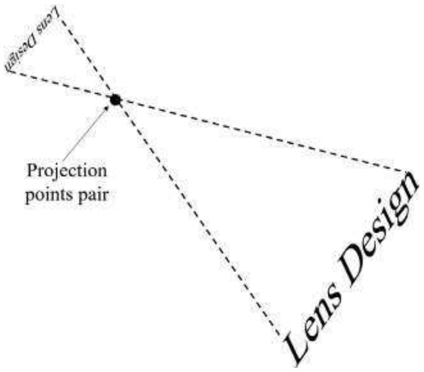

Figure 2.1 Central projection imaging where the object on the left is imaged on the right. In this case the projection points coincide in space.

possible mappings such as the equidistant mapping, $\bar{y}_i = f \cdot \theta$, or the orthographic mapping, $\bar{y}_i = f \cdot \sin(\theta)$. We are assuming that the object and image lay on planes perpendicular to the optical axis of the optical system. There are some applications that require the image to lay on a curved surface, and then the concept of classical imaging no longer applies.

The point is that lenses are designed to produce images which require a lens designer to be clear about what imaging means. Imaging is and will continue to be an important subject which substantially impacts lens design. What imaging is depends on system application.

2.2 First-Order Optics

The concept of first-order imaging arises from a first-order approximation to the path of a real ray. A real ray in homogenous media travels in straight lines, refracts according to Snell's law, $n' \sin(I') = n \sin(I)$, and its tracing considers the actual shape of the refracting surface. A first-order ray refracts according to a first-order approximation to Snell's law, $n'i' = ni$, and treats the optical surfaces as planar, but with refracting power, ϕ. To trace a first-order ray, the refraction and transfer equations are used:

$$n'u' = nu - y\phi \tag{2.1}$$

$$y' = y + u't, \tag{2.2}$$

where u and u' are the slopes of the ray before and after refraction, y is the ray height at the surface which is assumed planar but with optical power ϕ, n is the index of refraction, and t is the distance to the next surface.

In lens design we are concerned with first-order imaging, as obtained by tracing first-order rays, because it is equivalent to central projection imaging. In addition, first-order imaging establishes a model for a lens system where the cardinal points – these are the focal points, the nodal points, and the principal points – have specific ray properties and serve as useful references. Many calculations in lens design are done by tracing first-order rays and, therefore, an optical designer must be familiar with first-order optics. An example of a calculation in lens design software is what is known as a "solve" in which the program automatically sets the distance t from the last surface to the ideal image plane using $t = -y/u'$.

The space where the object resides is called the object space and is infinite in extent. Similarly, the space where the image resides is called the image space and is infinite in extent. An important structure in a lens system is the aperture stop. The aperture stop is assumed to be circular, to lay on a plane perpendicular to the optical axis, and it solely limits the amount of light for the on-axis beam. The aperture stop helps to well define a lens system; this is, light beams for every field point become well defined after they pass through the aperture stop. The image of the aperture stop in object space is defined as the entrance pupil, and the image of the aperture stop in image space is defined as the exit pupil. The pupils and the stop are optically conjugated, meaning that their locations and sizes satisfy the Newtonian or Gaussian equations that are summarized in Table 2.1. Another aperture that contributes to well define a lens system is the field stop. The field stop limits the field of view of a lens system, and ideally it is located at an image plane.

Rays that travel in a plane that contains the lens system axis of rotational symmetry are called meridional rays. Rays that do not travel in a meridional plane are called skew rays. Two important first-order rays are the marginal and chief rays. By definition, the marginal ray is a meridional ray that originates at the on-axis object point and passes through the edge of the aperture stop. The chief ray is a meridional ray that originates at the edge of the field of view and passes through

Cambridge University Press
978-1-108-49432-8 — Introduction to Lens Design
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Table 2.2 *First-order concepts*

Optical axis	The axis about which an optical system has rotational symmetry.
Object space	The space where the object resides, which is assumed infinite in extent.
Image space	The space where the image resides, which is assumed infinite in extent.
Aperture stop	The aperture that solely limits the amount of light for the axial light beam.
f	Front focal length.
f'	Rear focal length.
Optical power or Refractive power (ϕ)	$\phi = -\frac{n}{f} = \frac{n'}{f'}$; n is the index of refraction in object space, and n' is the index in image space. The unit of power is the diopter or 1/meter.
Effective focal length (EFL)	The inverse of the optical power.
$F/\#$, F-number	The effective focal length divided by the diameter of the entrance pupil. $F/\# = \frac{EFL}{2y_e}$
Lagrange invariant ($\mathcal{K}$)	It relates to the optical throughput or capacity of an optical system to transfer optical power. $\mathcal{K} = n\bar{u}y - nu\bar{y}$
Afocal	The focal lengths are not defined.
Telecentricity in object space	The image of the aperture stop in object space is at infinity. Equivalently, the chief ray in object space is parallel to the optical axis.
Telecentricity in image space	The image of the aperture stop in image space is at infinity. Equivalently, the chief ray in image space is parallel to the optical axis.
Transverse magnification (m)	The first-order ratio of the image size to the object size.

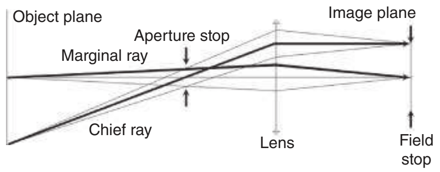

Figure 2.2 The marginal and chief rays (highlighted in bold) in relation to the aperture stop, the object and image planes, the field stop, and an ideal lens.

the center of the aperture stop. The trace of these two rays permits obtaining useful information about the imaging of an optical system. Figure 2.2 shows an object plane, an aperture stop, a lens, an image plane, and two sets of rays defining two light beams for the on-axis object point and for an off-axis point. In particular, Figure 2.2 illustrates the marginal and chief rays using bold rays. Table 2.2 provides a glossary of first-order concepts, and Table 2.3 provides a summary of first-order quantities. The Lagrange invariant, $\mathcal{K}$, is defined by

Table 2.3 *Marginal and chief first-order rays' related quantities*

Item	Marginal ray	Chief ray
Object/pupil distance	s	$\bar{s}$
Image/pupil distance	s'	$\bar{s}'$
Ray slope of incidence	$i = u - \alpha$	$\bar{i} = \bar{u} - \bar{\alpha}$
Ray height at surface	y	$\bar{y}$
	y_e	$\bar{y}_o$
	y_s	$\bar{y}_i$
Ray slope	$u = -y/s$	$\bar{u} = -\bar{y}/\bar{s}$
Normal line slope	$\alpha = -y/r = u - i$	$\bar{\alpha} = -\bar{y}/r = \bar{u} - \bar{i}$
Refraction invariant	$A = ni = n\left(\frac{1}{r} - \frac{1}{s}\right)y$	$\bar{A} = n\bar{i} = n\left(\frac{1}{r} - \frac{1}{\bar{s}}\right)\bar{y}$
Surface radius	r	
Surface vertex curvature	c	
Thickness to next surface	t	
Surface optical power	$\phi = \frac{n'-n}{r}$	
Lagrange invariant	$Ж = n\bar{u}y - nu\bar{y} = \bar{A}y - A\bar{y}$	

Quantities related to the chief ray carry a bar.
Primed quantities refer to the image space and un-primed to the object space.

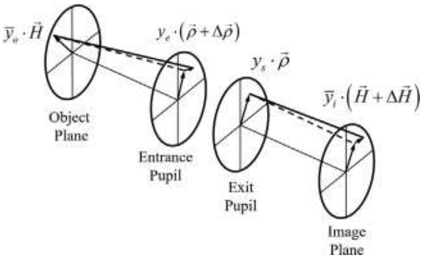

Figure 2.3 Model of an axially symmetric optical system showing the path of a first-order ray and the path of a real ray.

$Ж = n\bar{u}y - nu\bar{y}$, using the slope and height of the marginal and chief rays. Its value does not depend on the transverse plane where it is calculated. The amount of optical flux, or optical throughput, $T = \pi^2 Ж^2$, that can pass through an optical system is proportional to the square of the Lagrange invariant.

Figure 2.3 provides a representation of an optical system where the object and image planes and the entrance and exit pupils are shown. The solid line represents a real ray traveling from the object plane to the image plane, and the broken line represents a first-order ray. Two points are required to define a ray; the first point is defined by the field vector, $\vec{H}$, which lies in the object plane, and the second point is defined by the aperture vector, $\vec{\rho}$, which lies in the exit pupil plane. Both vectors are normalized so their magnitudes range from 0 to 1. To indicate an actual field point, the field vector is scaled by the chief ray height in object space, $\bar{y}_o$, and the aperture vector is scaled by the marginal ray height, y_s, at the exit pupil. In Figure 2.3 the real ray and the first-order ray coincide necessarily, per definition, at the object plane and at the exit pupil plane. Everywhere else these rays may differ in path. In particular, at the image plane they differ by the vector $\bar{y}_i \Delta \vec{H}$, and at the entrance pupil plane by the vector $y_e \Delta \vec{\rho}$. They differ at the image plane because of image defects known as image aberrations; similarly they differ at the entrance pupil because of pupil aberrations.

A lens designer may start a design with a first-order lens layout, as shown in Figure 2.4. Two ideal lenses with the same focal length form a 4*f* relay, as the distance between object and image is four-times the focal length of the lens elements. Such a layout provides useful information such as the ideal path of rays, the diameter of the lens elements, and the system's size.

In sum, first-order optics is equivalent to classical imaging and provides a basic structure to model a lens system.

2.3 Imaging Aberrations

Actual lens systems do not produce perfect imaging, but introduce image defects known as optical aberrations. Aberration can refer to wave aberration, transverse, longitudinal, or angular ray aberration.

In relation to Figure 2.5 the Optical Path Length (*OPL*) along a ray is defined as,

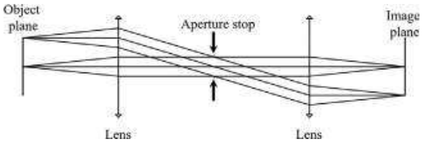

Figure 2.4 A doubly telecentric relay system in a first-order layout. Rays from on-axis and off-axis field points are shown. Two ideal positive lenses are schematically drawn as vertical lines with arrow ends.

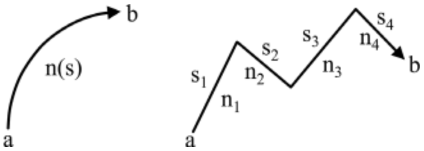

Figure 2.5 Left: Path of a ray in an inhomogeneous medium. Right: Path of a ray in several homogenous media.