Lens Design Fundamentals

Second Edition

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Chapter 4

Aberration Theory

4.1 INTRODUCTION

In the preceding chapter, imaging was considered to be ideal or stigmatic. This means that rays from a point source P that pass through an optical system will converge to a point located at its Gaussian image P'. In a like manner, the portion of wavefronts from P passing through the optical system will converge as portions of spherical wavefronts toward P'. In other words, the point sources are mapped onto the image surface as point images according to the laws of Gaussian image formation presented in the prior chapter. Deviations from ideal image formation are the result of defects or aberrations inherent in the optical system.

As will be discussed in this chapter, it is possible that the actual image $\tilde{P}'$ is formed at a location other than at P' which can be caused by field curvature and distortion while still forming a stigmatic image. When an optical system fails to form a point image of a point source in the Gaussian image plane, the rays do not pass through the same location and the converging wavefront is no longer spherical as a consequence of the optical system suffering aberrations. In this chapter, a mathematical description of the aberrations for symmetrical optical systems will be presented primarily from the viewpoint of ray deviation errors rather than wavefront errors. In the following chapters, each of the aberrations will be treated in significant detail in addition to their control during the optical design process.

4.2 SYMMETRICAL OPTICAL SYSTEMS

Figure 4.1 illustrates the basic elements of a symmetric optical system. This system is invariant under an arbitrary rotation about its optical axis (OA) and under reflection in any plane containing OA. Both of these symmetry characteristics are necessary properties of a symmetrical optical system.[1] A right-hand

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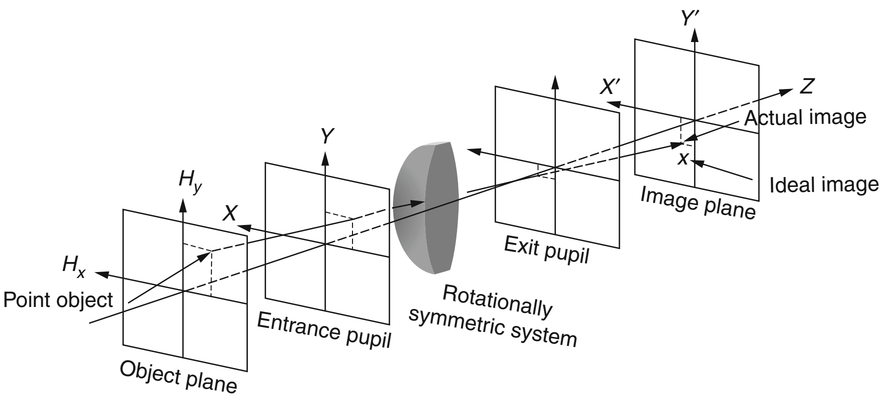

Figure 4.1 Basic elements of a symmetrical optical system.

Cartesian coordinate system is used where the optical axis is always taken to lie along the *z*-axis.[2] The ideal state of correction for a symmetrical optical system is when a system forms in the image plane (*IP*) normal to the optical axis a sharp and undistorted image of an object in the object plane (*OP*) orthogonal to the optical axis. These planes are designated as the image and object planes, respectively, and are conjugate since the optical system forms an image of one in the other. Unless otherwise specified, these planes should be considered to be orthogonal to the optical axis.

Consider for the moment an arbitrary point *P* in the object space of a symmetric system. In general the family of rays from *P* traversing the optical system will fail to pass through a unique point in the image space and the image of *P* formed by the system is said to be *astigmatic*, that is, to suffer from aberrations. If, on the other hand, all rays from *P* do pass through a unique point P' in the image space, the image of point *P* is said to be *stigmatic*.[3] From the definition of a symmetric system, it should be evident that if P' is the stigmatic image of some point *P* then the two points *P* and P' lie in a plane containing the optical axis. Now imagine that object points are constrained to lie in the object plane *OP* and that the images of all such points are stigmatic and that the object plane is stigmatically imaged by the system onto an image surface (in contrast to an image plane).

Again relying on the definition of a symmetric system, it is obvious that the stigmatic image of a plane object surface *OP*, which is normal to the optical axis of a symmetric system, is a surface of revolution about the optical axis. When this image surface of revolution is not planar, the imagery is considered to suffer an aberration or image defect known as *curvature of field* although there is no blurring of the image. Since the optical system is considered to be rotationally symmetric, we can arbitrarily select a reference plane that contains the optical axis. Referring to Figure 4.1, this plane is the Y-Z plane and is generally called the *tangential* or *meridional* plane.

Assume now that a stigmatic image of the object plane is formed in the image plane where the object has some geometrical shape. If the optical system forms an image having the same geometrical shape as the object to some scaling factor, the image is considered to be undistorted or be an accurate geometric representation of the object. Should the optical system form an image which is not geometrically similar to the object's shape, then the image is said to suffer distortion. When the system is free of distortion (undistorted), the ratio of image size to the corresponding object size is the *magnification m*, with the image for a positive lens being inverted and reverted with respect to the object. Let the object be a line extending from the origin of the object plane to the location denoted as point object in Figure 4.1 which has coordinates expressed as (H_x, H_y). The image size can be computed by

$$H'_x = mH_x \text{ and } H'_y = mH_y$$

since the line can be projected onto each axis and propagated independently without loss of generality since a paraxial skew ray is linearly separable into its orthogonal components.

It is evident from the preceding discussion that an ideal image of the object plane requires three conditions to be satisfied, namely, stigmatic image formation, no curvature of field, and no distortion. In contrast, an optical system having stigmatic image formation can still suffer the image defects of distortion and curvature of field.

As explained, an ideal optical system forms a perfect or stigmatic image which essentially means that rays emanating from a point source will be converged by the optical system to a point image, although curvature of field and distortion may be present. At this juncture, image quality will be discussed in strictly geometric terms. In later chapters, the impact of diffraction on image quality will be discussed.

The majority of this book addresses rotationally symmetric optical systems, their aberrations, and configurations. Figure 4.1 shows the generic geometry for such systems, which comprise five principal elements: the object plane, *entrance pupil*, lenses (including stop), *exit pupil*, and image plane.[4] A ray propagating through this system is specified by its object coordinates (H_x, H_y) and entrance pupil coordinates $(\rho_x, \rho_y) = \vec{\rho}$, or in polar coordinates (ρ, θ), as illustrated in Figure 4.2. This means that point P in the entrance pupil can be expressed by $X = \rho\cos(\theta)$ and $Y = \rho\sin(\theta)$ where θ is zero when $\vec{\rho}$ lies along the Y-axis.

This ray is incident on the image plane at (H'_x, H'_y) and displaced or aberrant from the ideal image location by $(\varepsilon_x, \varepsilon_y)$. Since the optical system is rotationally symmetric, the (point) object is assumed to always be located on the y-axis in the object plane, that is, $H \equiv (0, H_y)$. This means the ideal image is located along the y-axis in the image plane, that is, $h' = mH$ where m is the magnification. The actual

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