Seidel Aberrations 1.1

Prepared
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# Table of Contents

1. Introduction ................................................................. 3  
2. Spherical aberration ....................................................... 4 
3. Coma ........................................................................ 5 
4. Axial color ................................................................... 7 
5. Aberrations of a plate .................................................... 8
1 Introduction

A lens does not focus light perfectly throughout its entire image field. The error in destination of ray displays a dependency upon its location within the pupil of the lens. These imperfections are described by Seidel aberrations.\(^1\) As an example, the outer rays of a spherical surface are refracted too much; and consequently, the geometric spot size grows throughout the entire image. This degradation due to a spherical shape is called spherical aberration, which displays a cubic dependency between the spatial error at the image and position within the pupil of the lens. Variation in refractive index upon wavelength creates a discrepancy between ray destinations of different wavelengths. This aberration of color is called chromatic aberration. There are two orthogonal forms of chromatic aberration: axial color specifies a shift in focus along the optical axis, while lateral color specifies a shift in focus across the optical axis. An off-axis image occurs away from the central axis of the lens. A focused spot within the off-axis field frequently displays a fuzzy tail which resembles a comet. This off-axis aberration is called coma after the Greek word for hair komē. Coma is also due to spherical shape of the lens, but it only occurs at off-axis points within the image; it does not appear on-axis. Coma displays a parabolic dependency between radial error at the image and radial position within the pupil. Another off-axis aberration is astigmatism—it is created by the unequal spherical aberrations for off-axis portions of the image. The image field of a lens can significantly deviate from planar which creates defocus within the off-axis portion of the image. This effect is called field curvature, or Petzval curvature. Defocus displays a linear dependency between radial error at the image and radial position within the pupil. Defocus may also be caused by an error on focal length which is dependent upon the radius of every spherical surface within the system. The variable defocus within field curvature displays an increasing slope within the field for the linear dependency between radial error at the image and radial position within the pupil. The focal length can vary throughout the field so that a square object becomes a barrel or pin-cushion within the image. Such images can display uniform focus, but they can display distortion which is specified as either barrel distortion or pin-cushion distortion.

In total, there are eight primary characteristics of an optical system: focal length, axial chromatic aberration, lateral chromatic aberration, Petzval curvature, spherical aberration, coma, astigmatism, and distortion. A minimum of one degree-of-freedom within a lens design is required for control each primary characteristic. There are three types of degrees-of-freedom within a lens design which are: surface topography, thickness of material, and type of material. A plot of ray intercept curves displays the polynomial dependencies of destination error upon pupil position of rays within the imaging system. A third-order system displays ray intercept curves which are dominated by polynomials of third order or less, while a fifth-order system displays ray intercept plot which is dominated by fifth-order polynomials. Typically, a fifth-order system is more complex than a third-order system.

2  Spherical aberration

The spherical lens of Figure 1 displays a cubic ray-intercept plot, whereas a perfect lens would display a flat line at steady ordinate of zero. PY and PX are the positions of the ray within the entrance pupil at left, while EY and EX are the errors in position of the rays within destination at right. A cubic ray-intercept plot indicates spherical aberration.

Figure 1 Ray-intercept curves with the cubic polynomial of spherical aberration.
3 Coma

The aspheric lens of Figure 2 displays a parabolic ray-intercept plot in the off-axis field. A parabolic ray-intercept plot indicates coma. Coma is found only in off-axis fields.

Figure 2 Ray-intercept curves with the parabolic polynomial of coma in off-axis field.
The spot pattern of coma resembles a comet as seen below.

![Spot pattern of coma within aspheric lens.]

**Figure 3 Spot pattern of coma within aspheric lens.**
4 Axial color

Addition of second wavelength reveals axial color in which the ray intercept of secondary wavelength displays a finite linear slope while the primary wavelength ray intercept remains flat. A finite linear slope indicates defocus.

Figure 4 linear slope of axial color within aspheric lens.
5 Aberrations of a plate

A plate within a convergent ray-fan creates both spherical aberration and coma as displayed in Figure 5. Therefore, a plate should be placed within only collimated rays unless the lens is corrected for such a plate. The coma exceeds 100μm which is much larger than a CCD element of 10μm.

Figure 5 Aberrations of plate within convergent ray-fan
At a small convergence, the aberrations of a plate may become acceptable as seen in Figure 6. Only 3μm of coma is likely fine for a CCD element of 10μm.

Figure 6 Aberrations of plate within small convergent ray-fan
Addition of tilt to the plate creates a huge amount of astigmatism as seen in Figure 7 where the rays do focus within the plane of tilt. The 200μm of astigmatism far exceeds a CCD element of 10μm. Tilt of any element, even a lens creates astigmatism.
The spot pattern of astigmatism resembles an ellipse as seen below.

Figure 8 Spot pattern of astigmatism of tilted plate.