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Discussion

Aberration analysis of a concentric imaging spectrometer with a convex grating

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ABSTRACT

We analyze the ray-optical aberrations in a concentric imaging spectrometer composed of one convex grating and two concave mirrors of different radii. We assume that the system is generally not telecentric. First we derive aberration functions of Seidel and Buchdahl types for a bundle of rays converging to dispersed Gaussian images. Next we discuss the conditions in which the third and fifth-order ray aberrations are balanced. Finally we show that a concentric imaging spectrometer for use with a CCD detector can be optimized effectively in the neighborhood of a stigmatic condition. The stigmatic condition derived here can be useful in rapidly creating an initial design of a concentric imaging spectrometer with minimal aberrations.

1. Introduction

The spectral image can provide useful information on the inherent physical structure and chemical composition of material [1,2]. The imaging spectrometer of high spectral resolution has been developed for the purposes of anomaly detection, target recognition, and background characterization [3,4]. At present, imaging spectrometers are used for scientific research, medical diagnosis, environmental assessment, military purposes, food quality and safety control, and remote-sensing [5–9].

Specifically, it is known that concentric grating spectrometers provide better spatial and spectral resolutions in a compact form [10]. Lobb [11] analyzed the wavefront aberrations of a family of concentric grating spectrometers in which the aperture stop is located at the grating and the system is essentially telecentric in both object and image spaces. Chrisp [12] and Prieto-Blanco et al. [13] discussed the strategies to reduce astigmatism in Offner spectrometers. Recently Gonzales-Nunez et al. [14] performed an analytical approach to the design of Offner spectrometers with large angles of incidence. In their approach, the so-called light path function, instead of aberration functions of the conventional type [15,16], was employed not only to avoid the complicated analysis of intermediate images generated by a diffraction grating, but also to study the imaging properties. In the case of a computer-aided optical design, however, if once the general form of the optical system is known but the aberrations are reduced to acceptable tolerance levels, finite rays with large angles of incidence can be traced in the optical design program such as Code V (Synopsys Inc.), exactly according to Snell's law or a generalized form of it appropriate to diffractive optical elements. Hence it is of great importance to set up the initial design with an acceptable level of aberration before carrying out the optimization task. To do this, aberration functions of the conventional type, which are represented in terms of the paraxial parameters, are even useful, because they can give a relative simple relation to facilitate the initial design.

In this paper, we derive aberration functions of the Seidel and Buchdahl types [15,16] for a bundle of rays passing through the concentric imaging spectrometer which consists of one convex grating and two concave mirrors of different radii. We assume that the system is generally not telecentric in the sense that the aperture stop at the grating may be displaced from the back (or front) focal plane of the preceding (or following) optics. We also check further into the aberration-free conditions which enable us to rapidly create an initial design of concentric imaging spectrometer with minimal aberrations. In our approach, we first trace the path of a paraxial ray propagating from an off-axis object through the system to the corresponding Gaussian image, while the object is placed in the plane orthogonal to the optical axis, containing the common center of curvature of the grating and the mirrors. We then derive the expression of the working f-number

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compatible with a vignetting pupil. Next we formulate the wavefront aberrations for a bundle of rays converging to dispersed Gaussian images, where the terms of up to sixth order in aperture variables are taken into account. We find the transverse ray aberrations of up to fifth order by differentiating the function of wavefront aberration and also formulate the change of wavefront aberration caused by pupil aberration. We discuss the conditions in which the third and fifth-order ray aberrations are balanced. Finally we demonstrate that a concentric imaging spectrometer for use with a CCD array detector can be optimized effectively in the neighborhood of a stigmatic condition.

2. Paraxial analysis of a concentric imaging spectrometer

Fig. 1 shows a concentric-type imaging spectrometer consisting of one convex grating and two concave mirrors, in which C is the common center of curvature of the grating and the mirrors, V is the center of the grating taken as an aperture stop and a straight line connecting the two points C and V is the optical axis. The system is generally not telecentric in the sense that the aperture stop at the grating may be displaced from the back (or front) focal plane of the preceding (or following) optics. A bundle of rays emerging from an object point O at the zeroth plane is incident onto the first concave mirror and reflected toward the second convex grating. The rays diffracted by the grating are incident again onto the third concave mirror to make an image O' at the fourth plane. The local coordinate system is referenced to the tangent plane to each mirror, parallel to the $x$and y axes and the optical axis is chosen as the z axis. The grating lines ruled on the surface of the second mirror are parallel to the x axis and oscillating with a period of p along the y axis. The heights of O and O' are denoted by $\bar{y}_0$ and $\bar{y}_4$, respectively. $(0,\bar{y}_j)$ is the transverse coordinates at which a chief ray from O intersects the jth tangent plane, whereas $(x_j,\ y_j)$ is the transverse coordinates of an arbitrary ray at the jth tangent plane. The path of a paraxial ray propagating from O through the optical system to O' can be traced in the yz plane by using Abbe's zero invariant before and after the jth surface.

$$\frac{n_j'}{z_j'}-\frac{n_j'}{r_j}=\frac{n_j}{z_j}-\frac{n_j}{r_j},$$

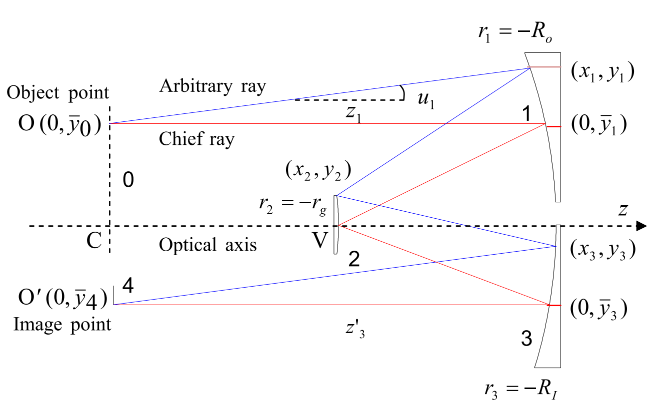

Fig. 1. An imaging spectrometer consisting of one convex grating and two concave mirrors. C is the common center of curvature of the grating and the mirrors, V is the center of the grating taken as an aperture stop and a straight line connecting the two points C and V is the optical axis. The local coordinate system is referenced to the tangent plane to each mirror. $(0,\ \bar{y}_j)$ is the transverse coordinates at which a chief ray from O intersects the jth tangent plane, whereas $(x_j,\ y_j)$ is the transverse coordinates of an arbitrary ray at the jth tangent plane. The object (or image) plane is located at z_1 (or z_3'). r_j is the radius of curvature of the jth mirror which is represented by the z-coordinate of its center of curvature, and we let $r_1=-R_o$, $r_2=-r_g$, and $r_3=-R_I$. u_1 is the angle of inclination of an arbitrary ray incident onto the first mirror

$$z_{j+1}=z_j'-d_j', \tag{1}$$

and the first-order approximation of Snell's law for the ray of diffracted order m at the jth surface

$$n_j'u_j'-\frac{m\lambda}{p_j}+\frac{n_j'}{r_j}y_j=\ n_ju_j+\frac{n_j}{r_j}y_j,$$
$$y_{j+1}=y_j+d_j'u_j', \tag{2}$$

for $j=0$ to 4 [15]. In the above, n_j (or n_j') denotes the refractive index of the medium in the object (or image) space of the jth mirror of which the sign is positive for the ray directed to the positive z axis. z_j (or z_j') is the z-coordinate of a local object (or image) which belongs to the jth mirror. r_j is the radius of curvature of the jth mirror which is represented by the z-coordinate of its center of curvature. d_j' is the distance from the jth surface to the $(j+1)$th surface of which the sign is positive when measured to the positive z direction. u_j (or u_j') is the angle of inclination of the ray incident onto (or emerging from) the jth surface of which the sign is positive when measured clockwise from the ray to the z axis. The grating spacing is assumed to be of $p_2=p$, while $p_j=\infty$ for $j\neq 2$. m is the order of diffraction and λ is the wavelength of light in vacuum. Similarly, the path of the paraxial ray in the xz plane can be traced by replacing y_j with x_j and putting $m=0$ in Eq. (2).

Now suppose that an object point O is placed in the plane orthogonal to the optical axis, containing the common center of curvature C as shown in many cases of application [12,13,17–19] and also let the system parameters be of $n_1=-n_1'=n_3=-n_3'=1$, $n_2=-n_2'=-1$, $z_1=r_1=-R_o$, $r_2=-r_g$, and $r_3=-R_I$. In that case, it follows from Eqs. (1) and (2) that the rays emerging from O with the transverse coordinates of $(0,\ \bar{y}_0)$, after being reflected by the entire system, converge to several points with the coordinates of

$$\bar{y}_4=-\left(\bar{y}_0-r_g\frac{m\lambda}{p}\right),\ \ z_3'=-R_I, \tag{3}$$

corresponding to a certain finite number of diffracted orders. The size of an image of diffracted order m corresponding to the spectral width $\Delta\lambda$ can be evaluated as

$$\Delta\bar{y}_4=r_g\frac{m\Delta\lambda}{p}. \tag{4}$$

In general, a bundle of rays from the off-axis object point suffers from vignetting. The upper marginal ray reflected from the first mirror reaches to below the top of the second mirror and the ray, when leaving the third mirror, has to go under the bottom of the second mirror. It is necessary, therefore, for the upper marginal ray entering the first mirror to have the angle of inclination smaller than

$$u_+\cong\left(\frac{2}{r_g}-\frac{2}{R_o}-\frac{1}{R_I}\right)\bar{y}_0-\left(1-\frac{r_g}{R_I}\right)\frac{m\lambda}{p}, \tag{5}$$

And the semi-diameter of the clear aperture of the second mirror is given by

$$h_g\cong\left(1-\frac{r_g}{R_I}\right)\left(\bar{y}_0-r_g\frac{m\lambda}{p}\right). \tag{6}$$

Next, the lower marginal ray goes past above the top of the second mirror to enter the first mirror and then the ray, after being reflected by the first mirror, has to meet the second mirror. Hence we find that the lower marginal ray entering the first mirror