Design study of two-aspherical-mirror anastigmat with reduced sensitivities to misalignments: correction of higher-order aberrations

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Abstract. A practical design method for correcting fifth and higher order aberration of two-aspherical-mirror optics was developed and applied to an imaging objective for soft-X-ray microscope. A sixth and eighth order deformation was applied to the both mirrors, and the deformation coefficients were optimized numerically to minimize a blur on the image plane. With this method, fifth or higher-order aberrations, which have remarkable effect on a fast soft-X-ray optics of a numerical aperture over 0.1, can be corrected without modifying third-order-aberration coefficients. A third-order aspherical design with a large misalignment tolerance was optimized to have a 50x magnification and a numerical aperture of 0.25, which resulted in a spatial resolution higher than 20 nm with tolerating a mirror decenter of 1µm.

1. Introduction

The Schwarzschild optics has been used for imaging experiments of microscopy in soft-X-ray region [1], however, the spatial resolution was still limited to a few micron range. The resolution limitation of the Schwarzschild optics can be attributed to its high alignment accuracy required. As Horikawa has pointed out, for imaging by a soft X-ray of 3.98 nm in wavelength, an allowable alignment error of the Schwarzschild mirrors falls within 300 nm for diffraction limit imaging[2]. Therefore, this high sensitivity to misalignments should be the dominant difficulty for implementing the mirror optics under various disturbances such as temperature drifts etc. It is known that this high sensitivity is inherent property of the two-spherical-mirror optics. As Erdos showed, there are only three aplanatic solutions in the two-spherical mirror system, and the Schwarzschild design is a unique solution of a real imaging[3]. This fact prevents an optical designer to seek a new practical solution with reduced sensitivity to misalignments in the spherical system.

The most promising way to overcome this difficulty is to seek for low alignment sensitivity configurations allowing larger misalignments by extending the spherical mirrors to aspherical ones. Since we have additional degree of freedom in the design parameters, wider possibilities with reduced sensitivity can be explored. Recently, we proposed new practical equations formulating third order aberrations in the case of two-aspherical-mirror anastigmat[4], and discovered the four new designs with large misalignment tolerance. The two-concave-mirror system, that is one of the new designs detailed in [4], has achieved reduction in sensitivity by a factor of twelve for the decenter of the mirrors, as compared to the Schwarzschild optics.
In the designing, performance of the optics was analyzed on the basis of the third-order aberration theory. In the case of the optics with relatively large numerical aperture, typically over 0.1, however, the higher-order effect cannot be ignored. In this paper we propose a practical method for correcting fifth and higher order aberration of the two-aspherical-mirror optics with large misalignment tolerance. In the design example, a magnification of -1/50 and a numerical aperture of 0.25 were taken as a typical design parameter.

2. Design method for higher-order aberration correction

In the following analysis, we employ a standard notation used in the optical designing of [4]. The optics we treat here can be represented by an object plane \((i=0)\), the first mirror \((i=1)\), the second mirror \((i=2)\), and an image plane \((i=3)\). The optical axis is taken as \(x\) in Cartesian coordinate with an object located in \(y-z\) plane. The surface figure of the \(i\)-th \((i=1\) or \(2)\) aspherical mirror can be represented by the following formula, employing a fourth-order deformation coefficient \(b_i\) to modify the radius of curvature \(r_i\), as

\[
x_i = \frac{y_i^2 + z_i^2}{2r_i} + \frac{1}{8} \left( \frac{1}{r_i^3} + b_i \right) \left( y_i^2 + z_i^2 \right)^2.
\]

(1)

In a two-aspherical-mirror anastigmat, configuration parameters and aberration coefficients to the third order can be described by one independent design parameter \(\gamma\), a marginal ray height ratio of the first mirror[4]. Shown in table 1 are the configuration parameters of the two-concave-mirror anastigmat with reduced sensitivities, which was found at \(\gamma = -0.650\).

**Table 1. Configuration parameters of the aspherical optics derived by the method in [4].**

| Radius of curvature | \(r_1\) (mm)     | -148.600    |
|---------------------|------------------|-------------|
|                     | \(r_2\) (mm)     | 26.677      |
| Mirror separation   | \(d_0\) (mm)     | 1031.748    |
|                     | \(d_1\) (mm)     | -41.649     |
|                     | \(d_2\) (mm)     | 9.901       |
| Mirror deformation  | \(b_1\) (mm\(^3\)) | 6.985×10\(^{-6}\) |
|                     | \(b_2\) (mm\(^3\)) | -2.366×10\(^{-5}\) |

A lateral aberration for on-axis object as a function of the numerical aperture, i.e., ray fans is shown in figure 1. We see that, in the case of third-order design of Table 1, which is shown by the solid curve, higher-order spherical aberration cannot be ignored when the numerical aperture |NA| exceeds 0.1.

For correction of higher-order aberration, we modify the figure equation by applying sixth and eighth deformation coefficients, \(c_6\) and \(c_8\) as

\[
x_i = \frac{y_i^2 + z_i^2}{2r_i} + \frac{1}{8} \left( \frac{1}{r_i^3} + b_i \right) \left( y_i^2 + z_i^2 \right)^2 + c_6 \left( y_i^2 + z_i^2 \right)^3 + c_8 \left( y_i^2 + z_i^2 \right)^4.
\]

(2)

The higher-order aberration can be corrected by optimizing the deformation coefficients, \(c_6\) and \(c_8\), on both mirrors. It should be noticed that, the third-order aberration coefficients of the system should not be affected by these higher-order terms, since these new terms will generate only fifth or higher-order
lateral aberration on the image plane. Thus, we can correct higher-order aberration of the aspherical
anastigmat shown in Table 1 by keeping a reduced sensitivity to the mirror misalignment, since the
sensitivity depends mainly on third-order coefficients for the spherical aberration $I_i$ and coma $II_i$ on the
both mirrors[4].

The deformation coefficients, $c_6$ and $c_8$, on both mirrors were optimized numerically to minimize
blurs on image plane. The optimization of the mirror deformation was calculated with a conventional
ray tracing method by using an optical designing software, CodeV[5]. Typical results of the
optimization are shown in Figure 1 with the dashed curve. The higher-order effect which is remarkable
on the third-order design, shown with solid curve, is clearly corrected below a lateral aberration of 10
nm after the optimization. Sensitivity to the misalignment was also confirmed by a ray tracing method.
Shown in Figure 2 is the lateral aberration of the higher-order-corrected optics with the second mirror
decenter of $E_2=1\mu m$. The aspherical-mirror system shown with triangle symbols keeps the aberration
below 20 nm, while the Schwarzschild system shown with square symbols is easily influenced by the
mirror decenter. The aberrations calculated with exact computer simulations, shown by the symbols,
also well coincide with the analytical description of a misaligned optics in [4], which is shown by solid
and dashed curves. The results verify the usefulness of our design method for correction of higher-
order aberration without modifying the sensitivity to a mirror misalignment.

Practical method for correcting higher-order aberration presented in this paper has been proved to
be useful for designing of two-aspherical-mirror anastigmat, particularly, of a soft-X-ray optics where
a large misalignment tolerance is essential for stable operation.

References

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