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Research on reflective zoom system with 3 mirrors

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ABSTRACT

This paper uses the third-order aberration theory to design a reflective zoom optical system. The advantage of this method is that, by solving a set of Seidel aberration coefficient functions, it allows the designer to achieve the initial construction parameters of the optical system, i.e., radii of curvature and separations between mirrors, etc. In order to verify the accuracy of this method, a prototype of a coaxial zoom optical system with three mirrors is designed. This paper introduces the manufacturing process of the prototype in detail, describes the procedures of aligning and experimenting, and analyzes the experiment results in the end. In this way, the feasibility of this method is confirmed.

1. Introduction

Reflective system has many useful properties, such as entirely free of chromatic aberrations, light weighted, and high thermal stability, etc. and is often used in aerospace systems. As early as in 1990, in order to meet the Boeing's requirements of the width of the field of view and the wide spectral imaging, R. Barry Johnson, James B. Hadaway, and Tom Burleson, where are from University of Alabama in Huntsville, had designed an all reflective zoom telephoto system with four elements [1]. This system, which is based on the first generation of MZT and then improved, is the second generation of MZT. The structure of system is Cassegrain-inverse Cassegrain, which is zoomed by displacing the two navigation power elements. In 1991, Cook [2] designed a kind of all reflective continuous zoom system which was based on the TMA optical system. The primary mirror and secondary mirror consist of a Cassegrain system and the system can be zoomed by displacing third elements. In 1992, through deviating the aperture from optical axis, Kebo [3] designed an unobscuration afocal zoom optical system with four mirrors, which was zoomed by displacing the primary mirror and secondary mirror. And the zoom ratio of two zoom system respectively are 3.6 (field of view 0.95–2°) and 0.5 (field of view 0.25–1°). Through deviating the aperture and field of view from optical axis, in 1995, Johnson [4] designed several unobscuration afocal zoom optical systems with three mirrors. And the secondary mirror and tertiary mirror can be displaced. The rms geometric blur diameter of a 4× zoom optical system which is one of these zoom systems, was found to be 45 urad in the wide FOV condition (2° by 2° and F/4). In 1997, Mann and Johnson [5] introduced the process of designing and analysis of all reflective zoom optical system which was based on the zoom system with 3 mirrors and applied to the field of infrared spectroscopy.

All of these systems are mechanical zoom which are zoomed by displacing one or two or three elements. But due to the limitation of the number of system components, the image plane of the system does not compensate. So these systems are all have disadvantages of the image plane of instability. In order to avoid the impact of image quality when the mirror was moved, Kristof Seidl [6] where are from Fraunhofer Institute for Photonic Microsystems designed an unobscured all reflective zoom optical system which was zoomed by changing the curvature radius of mirrors in 2009. And in 2010, he described the method of correction distortion [7] of this zoom system in detailed.

Above of these optical systems are all directed at specific application and was designed on the basis of the existing optical systems. Do not have a good scheme to calculate or choose the initial structure of zoom system. In order to solve this problem, in previous paper [8], the authors have proposed a simple method which solved the aberration equations for getting the initial structure of the reflective zoom optical system. Therefore, in order to verify the correctness and practicality of this theory, this paper has designed an all reflective zoom optical system with 3 mirrors by solving the aberration equations and has fabricated the prototype. The article described in detail the process of prototype, and installed and experimented of this prototype. Finally, the experimental results were analyzed and summarized to verify the feasibility of this theory.

2. Reflective zoom optical system design theory

This part uses Seidel aberration equations to design a zoom optical system [9]. The analytical expressions of Seidel aberration

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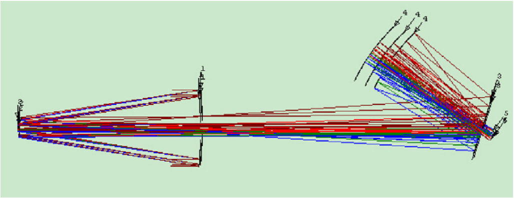

Fig. 1. Schematic diagram of optical system of prototype.

coefficients have the different types when we choose the different structural parameters. But in general, the structural parameters include mirrors' radii of curvature and intervals between mirrors. We set the stop aperture on the primary mirror and the object plane in infinite. So we can get Seidel aberration coefficients and the gauss parameters of system which only contain mirrors' radii of curvature and magnifications.

$$\begin{cases} S_{1i} = S_{1i}(r_1, r_2, r_3, r_4, \beta_{2i}\beta_{3i}\beta_4) = \text{target}_{1i} \\ S_{2i} = S_{2i}(r_1, r_2, r_3, r_4, \beta_{2i}\beta_{3i}\beta_4) = \text{target}_{2i} \\ S_{3i} = S_{3i}(r_1, r_2, r_3, r_4, \beta_{2i}\beta_{3i}\beta_4) = \text{target}_{3i} \\ S_{4i} = S_{4i}(r_1, r_2, r_3, r_4, \beta_{2i}\beta_{3i}\beta_4) = \text{target}_{4i} \end{cases} \tag{1}$$

where the target ($\text{target} = [\text{target}_{1i}, \text{target}_{2i}, \text{target}_{3i}, \text{target}_{4i}]^T$) stands for residual aberrations of the system in the ith position. According to the basic Gaussian formulas [10], the total focal length f' of the all reflective zoom system can be expressed as

$$f'_i = (-1)^n f'_1 \beta_{2i}\beta_{3i}\cdots\beta_{ni} \quad (i = 1, \ldots, k) \tag{2}$$

where $\beta_{ni} = l'_{ni}/l_{ni}$ is the magnification of the nth mirror at the ith position. The l'_{ni} and l_{ni} respectively stand for image distance and object distance of the nth mirror at the ith position.

The conjugate length L_i of the nth mirror is

$$L_{ni} = \left(\frac{1}{\beta_{ni}} - \beta_{ni}\right) f'_n \quad (i = 2, \ldots, k) \tag{3}$$

In order to get a stable image (as in the case of refractive cameras), mirrors 2 and 3 should have a fixed combined conjugate length during the movement [11]. So the following conditions must be satisfied

$$L = L_2 + L_3 = \left(\frac{1}{\beta_2} - \beta_2\right) f'_2 + \left(\frac{1}{\beta_3} - \beta_3\right) f'_3 = \text{Const} = L_1 \tag{4}$$

The separation between the secondary and tertiary mirror $d_{2,3}$, which is must be greater than 0.

$$d_{2,3} = l'_2 - l_3 = f'_2(1 - \beta_2) - f'_3\left(1 - \frac{1}{\beta_3}\right) > 0 \tag{5}$$

We can get the initial structure of the system if we have the residual aberrations of each configuration of the system and inconsideration of the limitation of the Eqs. (4) and (5).

3. The design example

3.1. Prototype

For the sake of checking the correction of the theory, we made an experimental prototype. The schematic diagram of the optical system is shown in Fig. 1. Its focal length is 450–1350 mm, such a system has a positive-negative-positive power distribution. Thereby, the total length of the system is short and the back focal length is relatively long. The final solution is obtained by adopting the design approach discussed above.

In the diagram, the optical surface with the label 1 is primary mirror. Its aperture is 85 mm, the central hole is 21 mm. And its surface is aspherical. The optical surface with label 2 is the secondary mirror. Its aperture is 16.04 mm and its surface is quadric. The surface labeled 3 is a folder mirror. It is used to avoid obstruction brought by image plane. The last surface is the tertiary mirror with the same surface type of primary mirror, and its aperture is 83.62 mm. In the zooming process for example, from short to long, the primary mirror keeps still and working as the fixed group. The secondary mirror, which acts as the zooming group of the system, linearly moves from left to right. In order to keep the image surface stable, the tertiary mirror acts as the compensating group and moves nonlinearly from right to left.

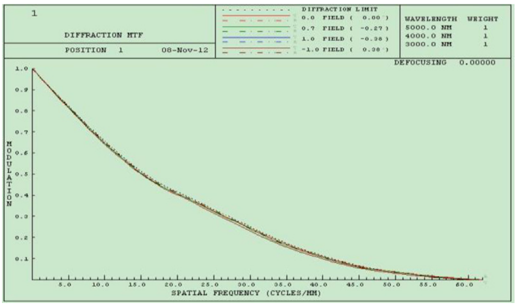

Fig. 2. MTF graph of short focal length.

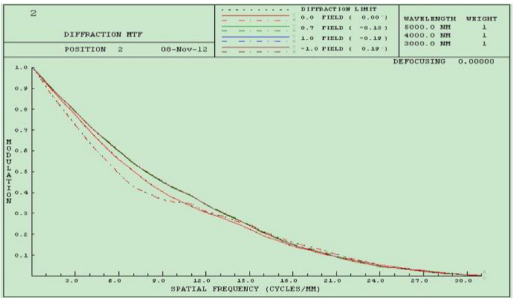

Fig. 3. MTF graph of middle focal length.

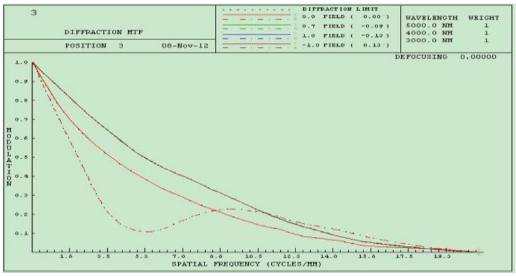

Fig. 4. MTF graph of long focal length.

The MTF graphs of the system of the three focal lengths are shown in Figs. 2–4 respectively. From these figures, it is evident that the image quality of the system achieves the defined diffraction limits. Some of the notable design parameters are listed in Table 1.

In order to achieve the diffraction limit over the whole field of view, the primary and tertiary mirrors are aspherical surfaces, and

Table 1
Design parameters of the example.

Focal length	450–1350 mm
Spectral bands	3–5 μm
Entrance diameter	85 mm
Field of view (FOV)	0.76°–0.26°