Design of Hybrid Refractive-Diffractive Objective with Super Wide Angle and Fast f-Number

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Abstract. To design a hybrid refractive-diffractive objective with super wide angle and fast f-number, the interrelationship of the objective parameters was analyzed and an initial conventional spherical system was achieved to fulfill the fundamental performance, then its distortion was corrected by the aspheric surface depositing far from the optical pupil and one of doublets was replaced by hybrid refractive-diffractive lens to reduce the size of the system. Using ZEMAX software, the final visible band objective with 100° FOV and f-number 2.5 was obtained by only 6 elements with a smaller size about 35 mm × 60 mm. Simulation shows that the MTF at 25 lp/mm is greater than 0.45 in the central field and 0.3 in the full field; the maximal distortion is less than 4%, much smaller than 35% of conventional system.

1. Introduction

In recent years, people pay more attention to the design of super wide angle optical system with fast f-number [1], it is believed to pick up enough information in image matching quality of spatial cameras. But the wide angle objective has larger barrel distortion that increases fast with the field of view (FOV), and it must be corrected to avoid wrong match, although it doesn’t affect the image definition. In addition, the optical system must be minimized to enhance the effective payload.

The hybrid refractive-diffractive objective designed by Russell Hudyma in Ref. [2] has 90° FOV and f-number 2.5. Its maximal distortion is 8%, total length is 75 mm, and its MTF is greater than 0.3 at 25 lp/mm in full FOV. In this paper, an objective with wider FOV, smaller distortion and compact size is proposed.

Considering the FOV, back working distance, f-number and illumination in the image plane, the Inverse telephoto was selected as the basal construction. The parameters were determined according to the application field and the suited CCD. The methods of correcting distortion and miniaturization were analyzed. A hybrid refractive-diffractive objective was finally obtained and the Monte Carlo analysis is carried out to examine the system tolerance.

2. Optical configuration

It is a challenge to design a super wide angle optical system with fast f-number [1]. The high resolution and strong light power can be obtained by fast f-number, but the aberration on-axis (namely spherical aberration) becomes hard to correct. The off-axis aberrations, especially the distortion may increase fast with FOV, that should be strictly restricted in image matching application, and the aberration balance is difficult.
To correct the off-axis aberrations, symmetry structure is better because lenses bend to the optical pupil (see Figure 1), transverse aberration is corrected automatically, the spherical aberration and the chromatic aberration are corrected by lens without focal power. But the marginal illumination at the image plane reduces fast due to the approximate equal of FOV in the object and image space. The illumination relation between the central and marginal of image plane follows the Eq. (1):

\[ E' = E_0' \cos^{\omega'} \]

\[ E' \] — Central illumination at the image plane;

\[ E_0' \] — Marginal illumination at the image plane;

\[ \omega' \] — Half field of view in the image space.

The marginal illumination at the image plane reduces to 20% of the central for 100° FOV. To achieve illumination uniformity at the image plane is also difficult, even if the vignette is applied.

Moreover, the symmetry structure with super wide angle, like Hypogon objective, Topogon objective, Pyccap25 objective, did not achieve a fast f-number.

Alternatively, the Inverse telephoto construction that consists of separate negative and positive lenses (see Figure 2) is suitable for an optical system with super wide angle. The incidence angle in back lens is reduced due to the divergence of front lens, so the aberration of back lens is easy corrected. For this construction, working distance is longer than the focal length, so match with CCD is insured. FOV in image space reduces with the inverse ratio of the front focal power to back, so the illumination uniformity at the image plane is better. Therefore, considering the working distance, f-number and illumination at the image plane, the Inverse telephoto construction is selected.

### 3. Parameters of the optical system

#### 3.1. Structure parameters

The visual band optical system has 100° FOV, f-number 2.5. 1/2 inch CCD with C optical interface is selected, i.e. its back working distance is 17.52 ± 0.18 mm, the image height must be matched up to CCD. According to the relation between the FOV of object space and image height shown in Eq. (2), if FOV and the size of CCD are selected, the effective focal length is determined.

\[ 2y' = 2f' \tan \omega' \]

\[ 2y' \] — Diagonal size of CCD;

\[ f' \] — Effective focal length;

\[ 2\omega \] — Full field of view in object space.

#### 3.2. Imaging quality parameters

Modulation transfer function (MTF), the most important integrative criterion of imaging evaluation for optical system, is determined according to application. A low-frequency characteristic is enough to distinguish object’s profile in spatial application of the optical system. The distortion does not affect the imaging definition, so it is not corrected in general, but it must be controlled less than 5% for the image match precision.

According to the above discussion, the main optical specifications are listed in Table 1.
Table 1. Specifications of the optical system.

| Parameter              | Specification |
|------------------------|---------------|
| Working band           | 486~656 nm    |
| Full field of view     | 100°          |
| F/#                    | F/2.5         |
| Back working distance  | 17.5 mm       |
| Image height           | 8.0 mm        |
| Focal length           | 3.3564 mm     |
| Distortion             | ≤5%           |
| MTF (25lp/mm)          | ≥0.45 (in the central field) |
| MTF (25lp/mm)          | ≥0.3 (in the full field)    |

4. Design of the optical system

4.1. Thin lens predesign

The predesign of the thin lens is to determine the assignment of focal powers \((f_a, f_b)\), separation of the groups \(d\) and back working distance \(b\) (see Figure 2). The correlations between them are shown in Eqs. (3) and (4).

\[
f_a = \frac{df}{(f - b)} \tag{3}
\]

\[
f_b = \frac{db}{d - (f - b)} \tag{4}
\]

Figure 3 describes the relationship between two focal lengths and group separation in Eqs. (3) and (4) (in this system focal length is 3.3564 mm and back working distance is 17.5 mm, for comparison, \(f_b\) is multiplied by constant -1). From the figure we know that two focal lengths increase with the group separation. To reduce the difficulty of design, a longer group separation is appropriate.

In addition, there is a correlation between the Petzval sum and the assignment of the thin lens group's focal lengths, shown in Eq. (5), the balance between them must be achieved.

\[
S_4 = J^2 \sum \frac{\varphi}{n} = J^2 \left( \frac{\varphi_a}{n_a} + \frac{\varphi_b}{n_b} \right) \tag{5}
\]

Figure 4 illustrates the relationship between the Petzval sum and group separation. It shows that “zero Petzval solution” appears at exceedingly long group separation, this may leads to optical system longer. But the reduction of the Petzval sum is slow when the group separation is longer than 35 mm. Based on the preceding analysis, the first order layout parameters of the thin lens are selected as in Table 2.
Table 2. First-order layout of the thin lens.

| Parameter | Value         |
|-----------|---------------|
| \( f_a \) | -10.6789 mm (K9) |
| \( f_b \) | 13.3150 mm (ZF5) |
| \( d \)   | 45 mm         |

4.2. Design of the conventional spherical system

Firstly, the fundamental performance was achieved by an initial conventional spherical system with inverted telephoto configuration, except the correction of distortion from front negative lenses. Figures 5, 6, 7 describe the system layout, MTF and distortion respectively: the size is \( \Phi 35 \text{ mm} \times 70 \text{ mm} \), the distortion is about 35% at full FOV, MTF at 25 lp/mm is greater than 0.7 in the full field. The next improvement for this system is focus on the distortion correction and size miniaturization.

4.3. Approach to correct the distortion

It is difficult to correct the distortion less than 5% to the super wide angle optical system, because the primary distortion rises proportionally with the cube of FOV. There are two methods to correct distortion. One is the digital correction: it can work very well, but is time-consuming and could not satisfy the real-time requirement [3].

The other method is the optical correction, i.e. the real-time method. It contains three main forms. The first is to utilize the optical structure shown in Figure 1, distortion is counteracted by the construction symmetry about optical pupil. The second is to use the field lens placed near the image plane [4], the distortion and field curve can be corrected and other aberrations are almost unaffected, but the back working distance is reduced. The third is to apply aspheric surface that has more freeness and makes the design more flexible. Considering the distortion, image quality, speed and working distance, the aspheric surface is introduced in system design.

4.4. Design of the hybrid refractive-diffractive optical system with aspheric surface

For the Inverse telephoto, the aberrations correlated with the aperture can be corrected by aspheric surface depositing near the optical pupil, and the aberrations correlated with the FOV can be corrected by aspheric surface depositing far from the optical pupil. Distortion is correlated with FOV, so the aspheric surface must be placed far from the optical pupil.

In ZEMAX software the model of the even aspheric surface is given by:
Figure 8. Layout of the hybrid refractive-diffractive optical system.

Figure 9. Distortion of the hybrid refractive-diffractive optical system.

Figure 10. MTF of the hybrid refractive-diffractive optical system.

Figure 11. Monte Carlo analysis of the hybrid refractive-diffractive optical system.

5. Tolerance analyze

To ensure image quality of the new design, the tolerance of the optical system was analyzed. There are three kinds factors in production process: materials, fabrication, assemblage. The tolerance assignment of the final optical system is listed in Table 3.

Figure 11 shows the MTF curve of the 20 random simulation results of the hybrid refractive-diffractive optical system through Monte Carlo analysis method with ZEMAX software. The figure shows that 95% of the results are in the tolerance zone, so the tolerance assignment of the system is feasible.
Table 3. Tolerance of the optical system.

| Tolerance                          | Value                      |
|-----------------------------------|----------------------------|
| Radius tolerance of the surface   | 0.02 mm                    |
| Local aperture ΔN                 | 0.2                        |
| Thickness tolerance Δd            | 0.05 mm                    |
| Decenter of the surface           | 0.01 mm                    |
| Tilt tolerance of the surface     | 0.01°                      |
| Refractive index tolerance Δn_d   | 2×10⁻⁴ (grade 4C)          |
| Abbe tolerance Δν                  | 0.2 (grade 2C)             |
| Decenter tolerance of the element | 0.03 mm                    |
| Tilt tolerance of the element     | 0.05°                      |

6. Conclusion
In this paper the important status of the objective with super wide angle for the spatial camera and the influence of the distortion for the image match precision are elaborated. The inverse telephoto was selected as basal structure, the distortion was corrected by an aspheric surface depositing far from the optical pupil and the miniaturization was achieved by using refractive-diffractive objective. The simulation experiment and tolerance analysis by ZEMAX software show that, compared with Russell Hudyma’s objective, the final visible band hybrid objective with f-number 2.5 has the same imaging definition, but the FOV is enhanced to 100°, the full FOV distortion is reduced to 4% and the configuration is more compact. Monte Carlo analysis on tolerance confirms the feasibility of the fabrication.

References
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