Conformal optical system design with a single fixed conic corrector*

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A conformal optical system refers to the one whose first optical surface conforms to both aerodynamic and imaging requirements. Appropriate correction is required because a conformal dome induces significant aberrations. This paper intends to explain that an effective solution to the easy-fabrication conic surface corrector compensates aberrations induced by a coaxial aspheric dome. A conformal optical system with an ellipsoid MgF_2 conformal dome, which has a fineness ratio of 2.0, is designed as an example. The field of regard angle is ±30 degrees with a ±2 degree instantaneous field of view. The system's ultimate value of modulation transfer function is close to the diffraction limit, which indicates that the performance of the conic conformal optical system with a fixed conic corrector meets the imaging requirements.

Keywords: conformal optics, dome, conic corrector, Risley prism

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1. Introduction

Conformal optical domes can greatly extend the range of the inner imaging system and the speed of aircrafts. These domes are characterized by outer window elements which conform to aerodynamic performance requirements. An aspheric outer shape which typically deviates greatly from spherical surface descriptions performs much better. However, the target images of interests are degraded because the aspheric dome induces a lot of varying aberrations in transmitting optical wavefront.[1]

In conventional correction methods, two types of correctors are commonly adopted to eliminate aberrations; the fixed corrector and the dynamic corrector. A fixed corrector contains one or a group of settled optical elements located behind the conformal dome, for instance, the Zernike-shaped corrector,[2] the Arch corrector[3] and the gradient-index progressive corrector.[4] A dynamic corrector is commonly complicated, for example, the gimbal based conical corrector,[5] the counter-rotating phase plates[6] and the deformable mirror arrays.[7] The above correction methods can improve the imaging performance; however, they greatly increase the weight and cost of the whole system. Most importantly, it is a tremendous challenge to fabricate and test these complicated correctors.

Therefore, it is necessary to study an improved corrector scheme which is simple, inexpensive and easy for industrial production. The present paper proposes an ordinary and effective method that a single fixed conic corrector is adopted for the coaxial aspheric dome and an example system is proposed subsequently which achieves high image quality.

2. Conic plate for dome aberration correction

2.1. Dome aberration analysis

As a typical conformal example, an ellipsoidal dome is followed by a perfect lens as shown in Fig. 1. The dome with a fineness ratio of 2 means that the value dividing the dome length by the dome base diameter is 2.[8] Figure 2 shows large amplitude Zernike aberrations across the field of regard (FOR). The dominant aberrations caused by an ellipsoidal dome are the 3rd order astigmatism (Z5) and coma (Z8) as shown in Fig. 2. The fundamental challenge is to find a basic optical structure to correct these aberrations.

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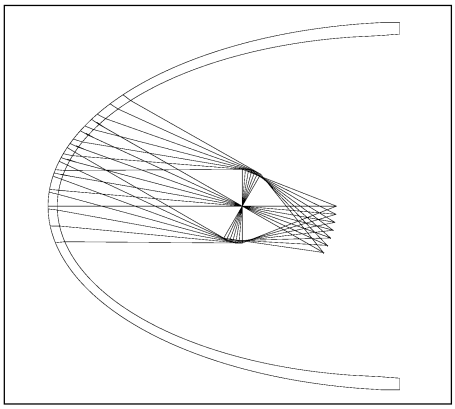


Fig. 1. Typical conformal model with a perfect lens.

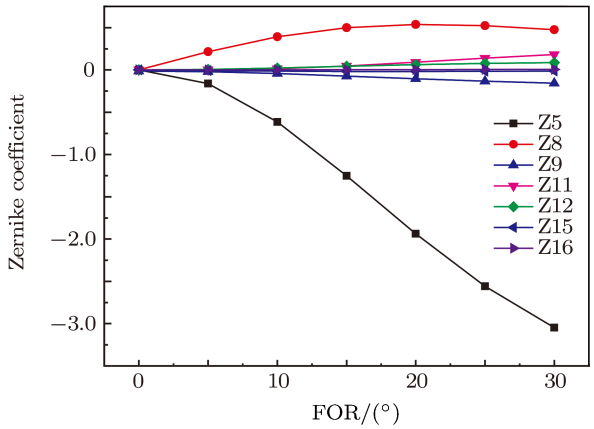


Fig. 2. (colour online) Selected Zernike aberrations.

2.2. Theory of primary aberration for aspheric surface

The aberration characteristics of the coaxial aspheric system are similar to that of the spherical system except the distribution among surfaces. To calculate the primary aberration distribution of the ordinary aspheric surface, one aspheric surface can be regarded as an overlap of one spherical surface and one zero central thickness plate as shown in Fig. 3, where z axis is the optic axis, r axis is the meridian plane coordinate axis, O is the origin of the coordinate, r_0 is the datum plane radius, C is the center of curvature, Δz is thinness increment of the zero center thickness plate and n and n' are material refractive index before and after the surface respectively.

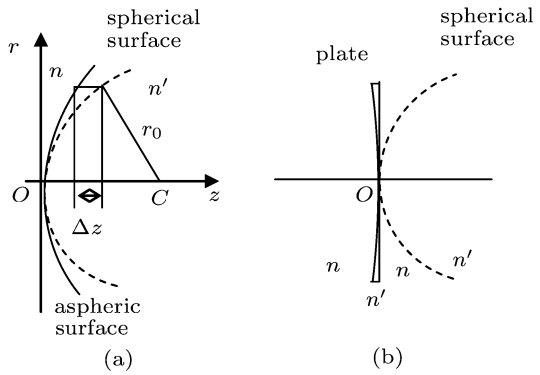


Fig. 3. Overlap of (a) one spherical surface and (b) one zero central thickness plate.

For a spherical surface which has the same axial curvature radius r_0, the Seidel aberration coefficients increment of the aspheric surface can be described as[9]

$$\Delta S_2 = -\frac{(n'-n)e^2}{r_0^3}h^3 \cdot h_z, \tag{1}$$

$$\Delta S_3 = -\frac{(n'-n)e^2}{r_0^3}h^2 \cdot h_z^2, \tag{2}$$

where h is the intersection height of the paraxial ray on the aspheric plate, h_z is the intersection height of the chief ray on the aspheric plate and e^2 is conic deforming ratio.

The additional aberrations induced by aspheric surface such as typical ellipsoid ($0 < e^2 < 1$) and paraboloid ($e^2 = 1$) could be described by the above expressions. Because ΔS_2 and ΔS_3 are both in direct proportion to $-e^2$, an oblate surface ($e^2 < 0$) has the ability to correct one of additive coma and astigmatism abberations. The conceptual layout of a single conic surface with a perfect lens is shown in Fig. 4, where $r_0 = 40$ mm and the thickness between the stop surface and the conic surface is 30 mm. For different values of e^2, the different 5th and 8th Zernike coefficients are plotted in Fig. 5. The opposite signed coma and astigmatism aberrations can be cancelled out for different conic surfaces.

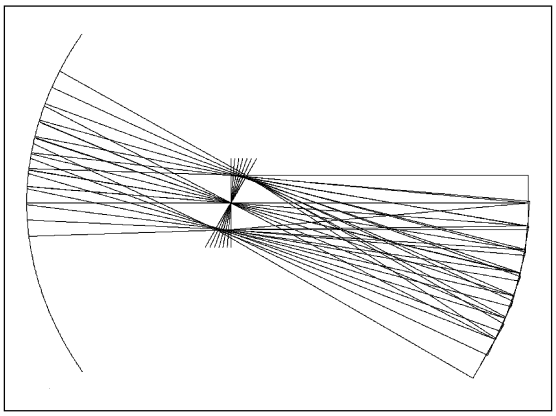


Fig. 4. Single conic surface with perfect lens.

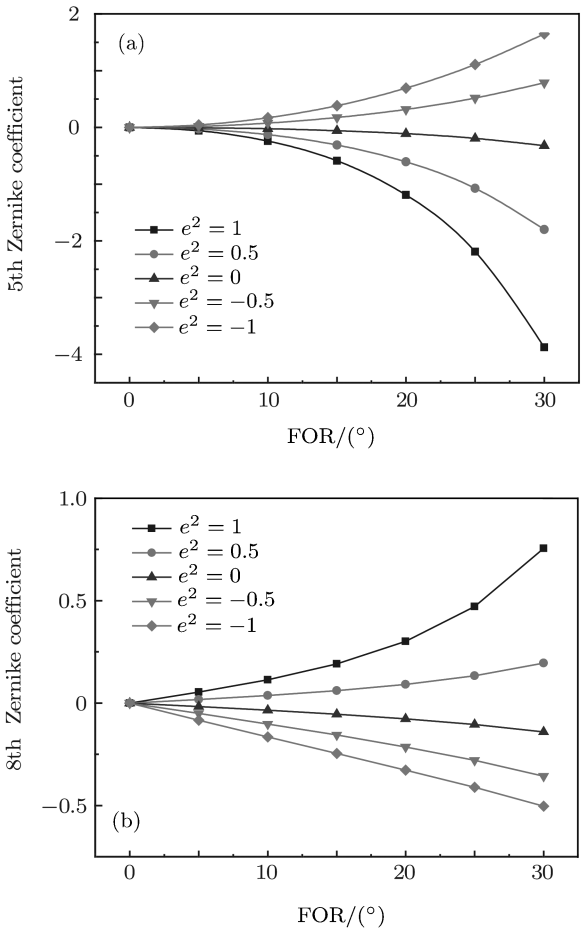


Fig. 5. The 5th and 8th Zernike coefficients for different e^2: (a) Z5, (b) Z8.

Aberrations in the optical system are induced by the combined contribution of each refractive surface but not a simple summation. Aberration behind a surface falls into two parts: one comes from the surface itself, the other is the objective aberration multiplied by surface transfer magnification. We suppose that two or more conic surfaces could correct the additional aberrations induced by ellipsoid or paraboloid conformal dome with appropriate aperture position.

2.3. Conic plate corrector for ellipsoid conformal dome of 2.0 fineness ratio

An ellipsoid conformal MgF_2 dome with a fineness ratio of 2.0 is to be compensated in this design. We take advantage of the powerful features of commercially-available optical design software to optimize the conic corrector. The system is followed by a perfect lens with 100 mm focal length as shown in Fig. 6. Zernike aberrations are analysed with and without the corrector as shown in Fig. 7. We can find that the coma and astigmatism aberrations have been compensated greatly. Actually the diffraction limit image quality is achieved.

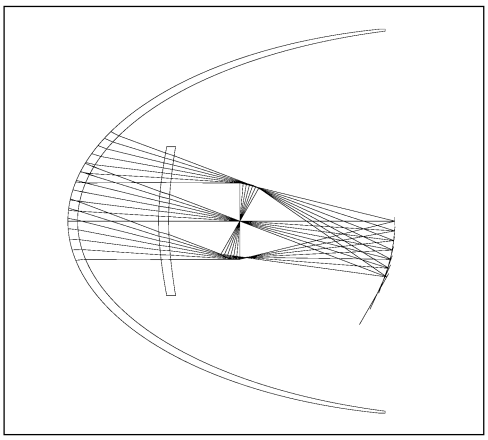


Fig. 6. Ellipsoid conformal MgF_2 dome with one conic corrector.

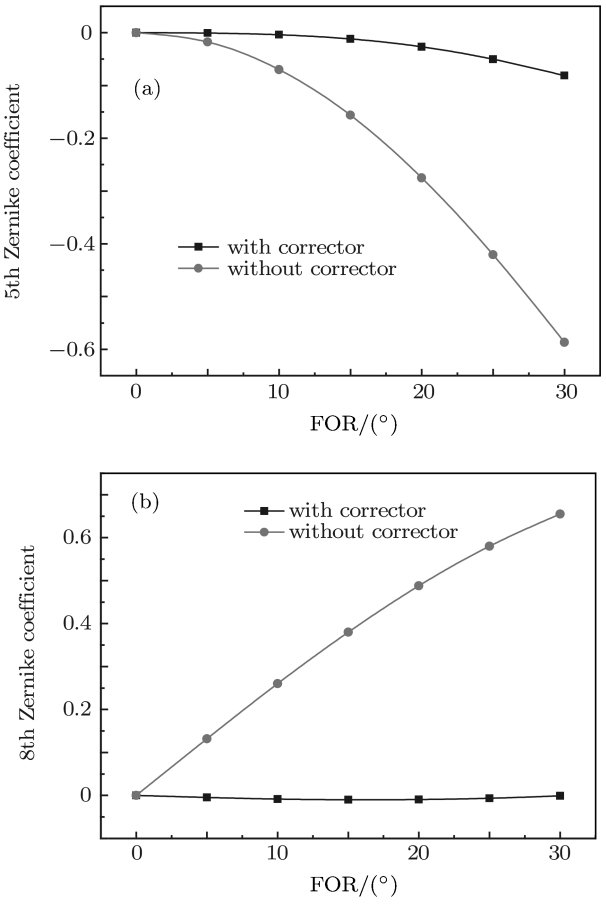


Fig. 7. The 5th and 8th Zernike aberrations with and without corrector: (a) Z5, (b) Z8.

3. Utilization of single conic corrector in a conformal optical system

3.1. Design specifications

A complete conformal optical system with MgF_2 ellipsoid dome, conic corrector, achromatic counter rotating Risley prisms and imaging system was designed, which is shown in Fig. 8. The instantaneous field of view (IFOV) is $\pm 2^\circ$ and the FOR is $\pm 30^\circ$. The dome fineness ratio is 2.0 and the conic correctors are similar to those analysed in Section 2.3. The design wavelength is from 3800 nm to 5000 nm and it has an 80 mm focal length with an F/# of 2.0.

3.2. Design methodology

Space in the aircraft equipments is cabined, so it is highly desirable to limit the number of motors used for field scan and aberration correction. A pair of identical rotating achromatic prisms optical system[10,11] known as Risley, is adopted for scanning targets.[12,13] The subsequent imaging system adopts a secondary imaging structure. It has 100% cold shield efficiency and can reduce the radial size of the system. The final system depicted in Fig. 8 is the result of a stepwise design process. First, one double-conic plate corrector is introduced to compensate the aberrations induced by the front dome. Next, a spherical element is added to control field curvature. Then we use a pair of achromatic counter-rotating prisms for FOR scan. Ultimate optimization of the complete system for all 0°, $\pm 1.4^\circ$ and $\pm 2^\circ$ IFOV at three different FOR results in the final design.

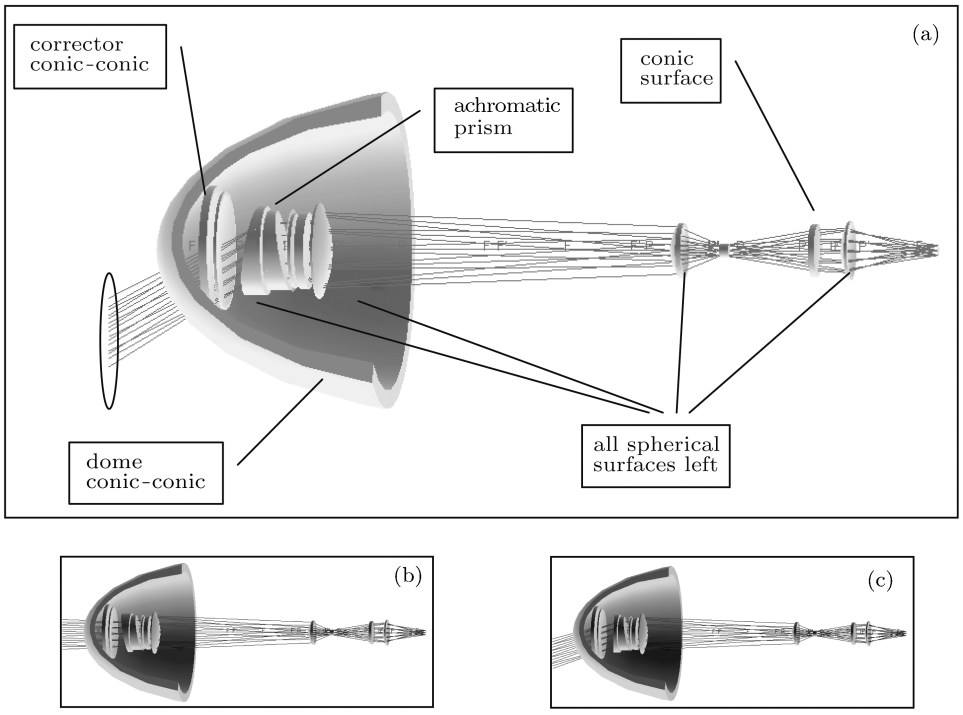


Fig. 8. Optical design using conic corrector to compensate conformal dome aberrations: (a) FOR is 30°, (b) FOR is 0°, (c) FOR is 20°.

3.3. Results

The transverse ray fan plots for the complete optical system are shown in Fig. 9. The system's ultimate modulation transfer function is approximate to diffraction limit as shown in Fig. 10, which indicates that performances of the conformal optical system have met the imaging requirements with single fixed conic corrector.

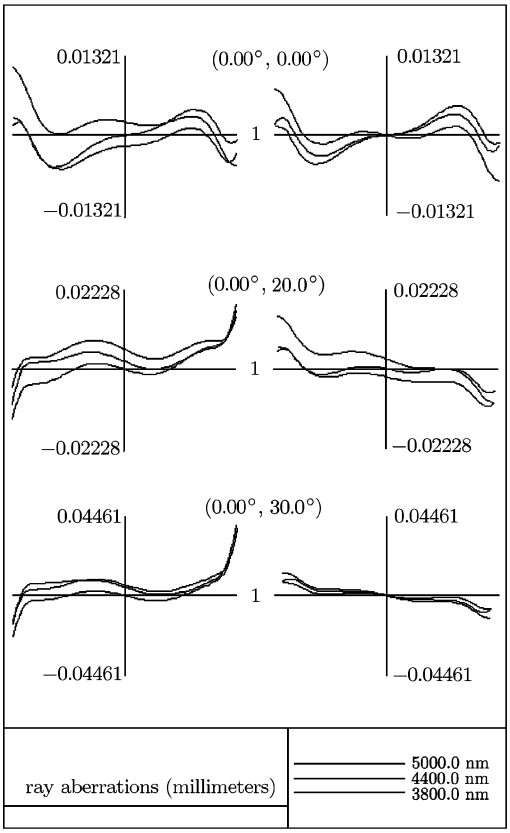
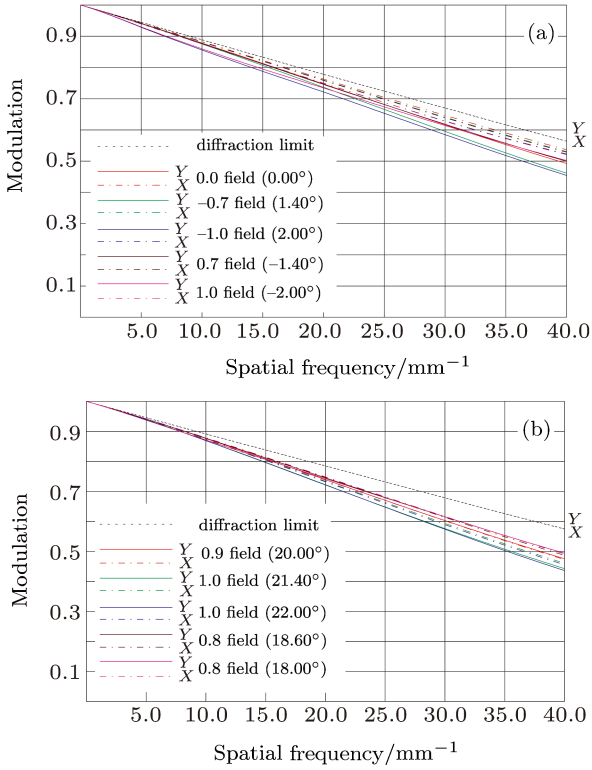


Fig. 9. Transverse ray fan plots for 0, 20 and 30° FOR.



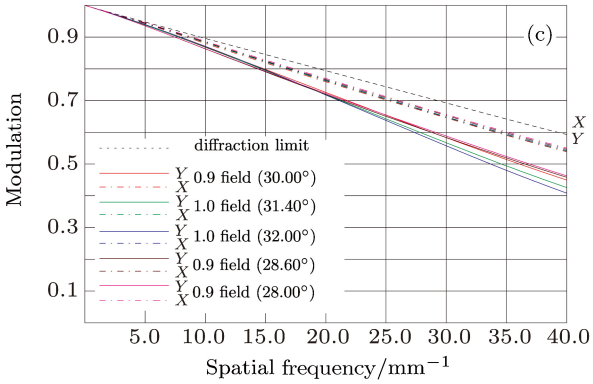


Fig. 10. (colour online) System's ultimate values of modulation transfer functions: (a) FOR is 0°, (b) FOR is 20°, (c) FOR is 30°.

4. Conclusions

We have shown that the fixed single conic surface correction is a good method for compensating the aberrations arising in the coaxial aspheric conformal optical systems. This optical system provides a practical, easy-fabrication and low-cost scheme for conic dome. Moreover, it is a small package without the extra servomotors which is adopted to the rigorous working environment in aircrafts.

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