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Aspheric dome optical system design using a wedge-shaped prism for the imaging system

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ABSTRACT

An aspheric dome was designed and the aberration characteristics of the dome were analyzed by Zernike aberration theory. A novel design method that a single wedge-shaped freeform surface (FFS) prism is adopted as the imaging lens for the system is presented. The design made the number of the system's elements and the length and weight of the system decrease, and the system center obscuration are exempted. A complete mid-infrared optical system with an MgF_2 ellipsoidal dome is designed as an example. The ultimate performance indicates that this design met the requirements on imaging properties of an airborne detection system.

1. Introduction

Compared to traditional optical domes whose shapes are spherical or flat, aspheric domes effectively reduce drag, increase the speed and flying range of the aircraft such as missiles and jet fighters, hence they are drawing growing attention in recent years [1]. The shape of the aspheric dome might be an ellipse, torus, ogive or other aspheric formulas that produce a higher fineness ratio [2,3]. But the domes with these shapes induce non-central symmetry aberrations that change significantly with look angles [4]. Generally one or two aberration correcting lenses are adopted to overcome this problem [5,6].

After using correcting components, some aberrations remain and must be compensated by the rear imaging lens group, so most imaging systems in aspheric dome systems are actually combinations of "corrector" and "imaging lens". The routine imaging group in aircrafts are catadioptric or purely dioptric. For instance, Li et al. adopted the catadioptric Cassegrain telescope with a deformable secondary mirror as the imaging system in the conformal optical system; [7] Chang et al. explored the dioptric group of lens for the imaging system in an ellipsoidal dome system [8]. The catadioptric configuration makes the whole optical system very compact, but the alignment of the secondary mirror is relatively complex and the obscuration caused by this mirror will induce a drop in the value of modulation transfer function (MTF), which conflicts to the need of high-resolution for seeker optical systems. The dioptric configuration is non-obscuration and has no difficult in alignment, but it leads to an excessive system length and number of lens, which is not adapted to the cabined inner space of air vehicles. Therefore, it is necessary to study an improved scheme to design an imaging system that possesses strong points of both catadioptric and dioptric structures but no drawbacks of them.

Ordinarily, most researchers are interesting in aberration correcting devices with parallel exiting rays; few studies focusing on imaging systems in aircrafts have been conducted. The paper proposes a novel and effective method that a single wedge-shaped FFS prism is adopted as the imaging lens for the coaxial aspheric dome, and an example system is proposed subsequently which achieves high image quality. The wedge-shaped prism as imaging lens has irreplaceable advantages, such as providing great design freedom, reducing the number of units, decreasing the length and weight of the system and avoiding the system center obscuration.

2. Analysis and preliminary correction for the aberrations induced by the dome

2.1. Aberration characteristics of the aspheric dome

Aberrations from the aspheric dome vary with the scanning angles. In order to analyse the optical system on different gimbal angles, the system should be designed at different zoom positions. Fig. 1 shows an ellipsoidal dome with a perfect lens at 9 zoom

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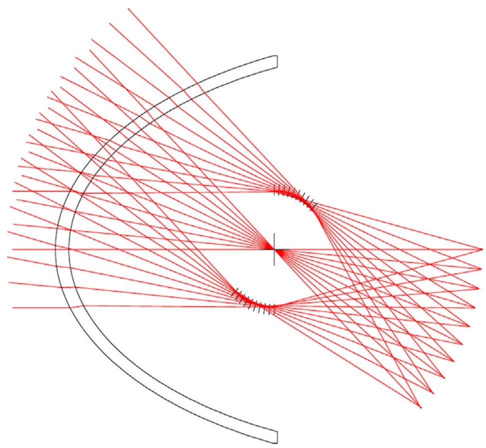

Fig. 1. Layout of the ellipsoidal dome with a perfect lens for all zoom positions.

Table 1
Parameters in the baseline dome.

Parameters	Value
Dome fineness ratio, *L*/*D*	1.0
Outer surface diameter, *D*	120 mm
Outer surface length, *L*	120 mm
Surface conic constant, *k*	−0.75
Thickness, *t*	4 mm
Material	MgF_2

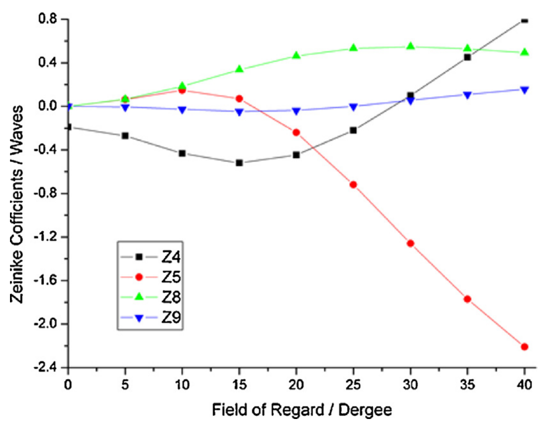

Fig. 2. Aberrations Z_4, Z_5, Z_8, and Z_9 versus field of regard (FOR) for the dome.

positions at gimbal angles from 0° to 40°in 5° increments. The specific parameters of the baseline conformal dome are listed in Table 1. As is customary, we characterize aberrations of the dome by decomposing the wavefront at the exit pupil into fringe Zernike polynomials [3]. Fig. 2 shows plots of aberrations versus the FOR angle. The dominant aberrations caused by the dome are focus (Z_4), coma (Z_8) and astigmatism (Z_5).

2.2. Preliminary aberration correction for the ellipsoidal dome

Considering the limited space behind the dome, only a single fixed corrector is used for compensating Z_5 and Z_8 in this design. Both of the front and rear surfaces of this lens are even ashpere surfaces. The combination of the dome and corrector for nine zoom positions is indicated in Fig. 3, and the imaging system is still represented by an *F*#/2 perfect lens. The curves for residual aberrations versus the look angle are plotted in Fig. 4. As shown in Fig. 4, astigmatism and coma are greatly eliminated due to utilization of the fixed corrector; now the system is dominated by approximately 2 waves of focus (Z_4) and 0.5 wave of spherical aberration (Z_9), which must be compensated by the rear imaging system.

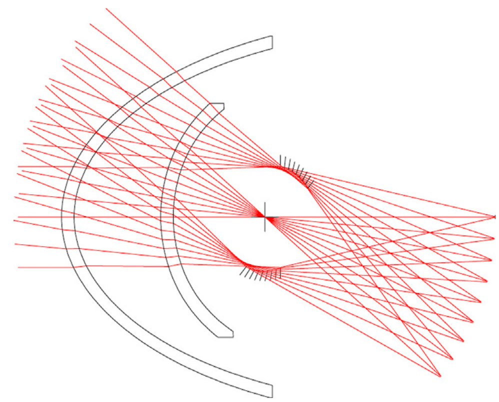

Fig. 3. Layout of the ellipsoidal dome with a fixed corrector and a perfect lens.

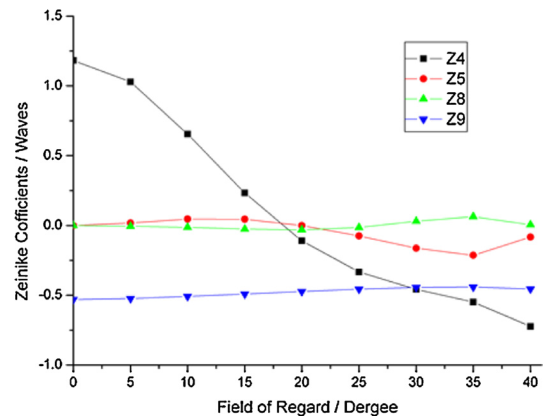

Fig. 4. Residual aberrations versus FOR for the dome with a fixed corrector.

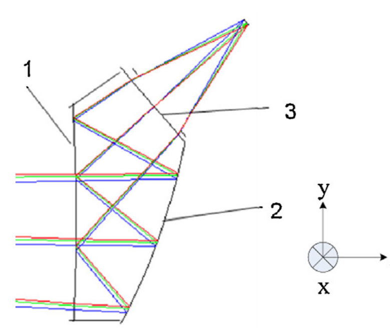

Fig. 5. Wedge-shaped prism consisting of three surfaces.

3. Residual aberration correction technology

Formerly the wedge-shaped prism is commonly used in design of optical see-through head-mounted display [9]. This element has a number of surfaces, including ashpere and freeform surfaces. Because all of the surface coefficient and the decenter and tilt of each surface can be optimization variables in optical design process, one single wedge-shaped FFS prism plays well in correcting aberrations. Moreover, multiple refraction and reflections in the prism greatly decrease the length and the number of the elements for the whole system. In the paper a FFS prism is employed to be the imaging lens in the ellipsoidal dome optical system.