Vol 18 No 2, February 2009
1674-1056/2009/18(02)/0565-06

Chinese Physics B

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Conformal optical design with combination of static and dynamic aberration corrections*

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(Received 3 May 2008; revised manuscript received 14 July 2008)

Conformal domes that are shaped to meet aerodynamic requirements can increase range and speed for the host platform. Because these domes typically deviate greatly from spherical surface descriptions, a variety of aberrations are induced which vary with the field-of-regard (FOR) angle. A system for correcting optical aberrations created by a conformal dome has an outer surface and an inner surface. Optimizing the inner surface is regard as static aberration correction. A deformable mirror is placed at the position of the secondary mirror in the two-mirror all reflective imaging system, which is the dynamic aberration correction. An ellipsoidal MgF2 conformal dome with a fineness ratio of 1.0 is designed as an example. The FOR angle is 0°–30°, and the design wavelength is 4 μm. After the optimization at 7 zoom positions by using the design tools Code V, the root-mean-square (RMS) spot size is reduced to approximately 0.99 to 1.48 times the diffraction limit. The design results show that the performances of the conformal optical systems can be greatly improved by the combination of the static correction and the dynamic correction.

Keywords: conformal domes, Zernike polynomial surface, deformable mirror, aberration correction

PACC: 4215E

1. Introduction

Conformal optics can be defined as optical systems that are designed with regard to the operational environment as the primary consideration and the optical imaging properties as a secondary concern.[1] Missile optical sensors must be isolated from the environment to ensure their proper function and aerodynamic performance. Conformal domes are characterized by their external optical surfaces that are optimally to minimize drag, increase missile velocity and extend operational range, thereby achieving highly aspheric dome geometries that are more elongated into some shapes, such as ellipses, hyperbolas, splines, or other forms that allow a higher fineness ratio and a smooth in airframe.

Unfortunately, these highly aspheric dome surfaces have a major disadvantage that they can produce large aberrations in transmitting optical wavefront. In addition, the inherent asymmetry of conformal surfaces leads to variation in the aberration content presented to the optical sensor as it is gimbaled across the field-of-regard (FOR).[2]

In conventional correction methods, some additional correctors are often added into the conformal systems, such as fixed correctors, arch correctors or some other aberration generators. Although those correction methods can greatly improve the imaging performance, they may increase the weight and the length of the whole conformal optical systems. So the present paper is to propose another method in which the static correction and the dynamic correction are combined, which can be achieved by systems themselves without adding any other corrector into them.

2. Design consideration

In design, the front part and the rear part of a conformal optical system should be considered separately. The front part is a conformal dome upstream from the imaging system. Aberrations from the conformal dome vary with the FOR angle. In order to make the imaging system scan different fields of regard, the system should be designed at different zoom positions. The default analysis functions and optimization are operated simultaneously over all defined zoom positions. Figure 1(a) shows a missile seeker

*Project supported by the National High Technology Research and Development Program of China (Grant No 2006AA012339).
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with a conformal dome at 8 zoom positions at FOR angles form 0° to 35° in 5° increments. The imaging system is a perfect lens. The field-of-view (FOV) is a feature of the imaging system, which rotates behind the conformal dome to achieve the full FOR by imaging through the dome at different look angles, see Fig.1(b).

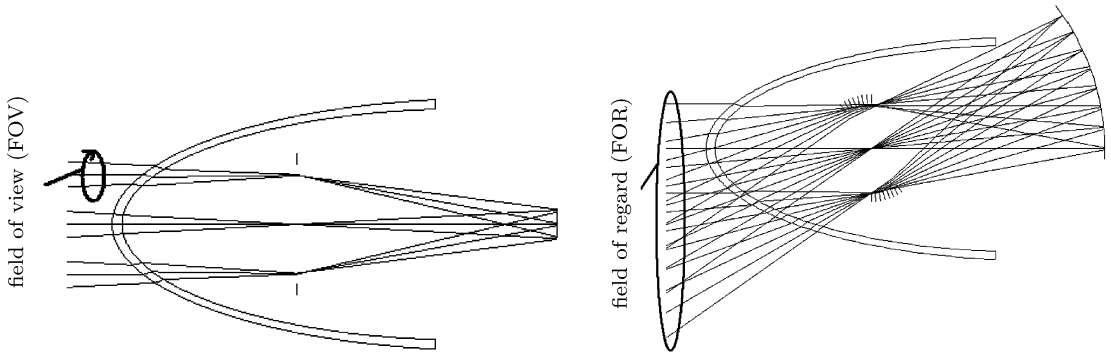


Fig.1. Conformal dome with 7 zoom positions over 60° full FOR (a) and conformal dome for 0° FOR with 2° full FOV (b).

2.1. Static aberration correction by optimizing the inner surface of conformal dome

A conformal dome includes an outer surface and an inner surface. The outer surface is shaped into an ellipsoidal surface. The inner surface is also ellipsoidal with the same conic constant as that of the outer surface, but with higher order Zernike terms. So the inner surface has a complex aspheric surface which is Zernike polynomial surface. The mathematical expression of the inner surface sag in Code V is given as follows:[3]

$$Z_{\text{sag}} = \frac{c\rho^2}{1+\sqrt{1-(K+1)c^2\rho^2}} + \sum_{j=1}^{66} c_{j+1} z_j(\rho,\theta) \quad (1)$$

where c denotes the curvature and equals 1/radius, $\rho^2 = x^2 + y^2$, and k is the conic constant.

A convenient property of the Zernike polynomials is that they are mutually orthogonal over a unit circle. Wavefront aberrations over a circular optical aperture can be conveniently described with Zernike polynomials; some classical aberrations such as spherical aberration, astigmatism, coma, and the like, are related to certain Zernike polynomial terms. Therefore it will be possible to design a Zernike polynomial inner surface that is targeted towards specific Zernike aberrations.

2.2. Dynamic aberration correction by using a deformable mirror (DM)

Deformable mirrors (DMs) are essentially reflective surfaces that are electromechanically manipulated to produce desired surface profiles. They can be used in adaptive optical systems to generate the Zernike-mode wavefront to compensate for the corresponding aberrations. In the case of conformal optical systems, the DMs can be used to create aberrations to compensate for those introduced by conformal domes.[4]

Micro-electromechanical system (MEMS) DMs which are light in weight and low in cost are preferred to use in the conformal missile systems. The MEMS DM is a newly developed device based on silicon micromachining technology with the advantages of compactness and low-cost.[5] Figure 2(a) shows a schematic diagram of the continuous surface MEMS DM that is used in this study. There are 37 electrostatic electrodes underneath the membrane working as actuators of the DMs with their layout shown in Fig.2(b). When the voltage is applied to the electrodes and the mirror membrane, the electrostatic force pulls down the membrane, thereby modulating the shape of the mirror surface. Desired mirror surface shapes can be obtained by applying appropriate driving voltages to the 37 electrodes.

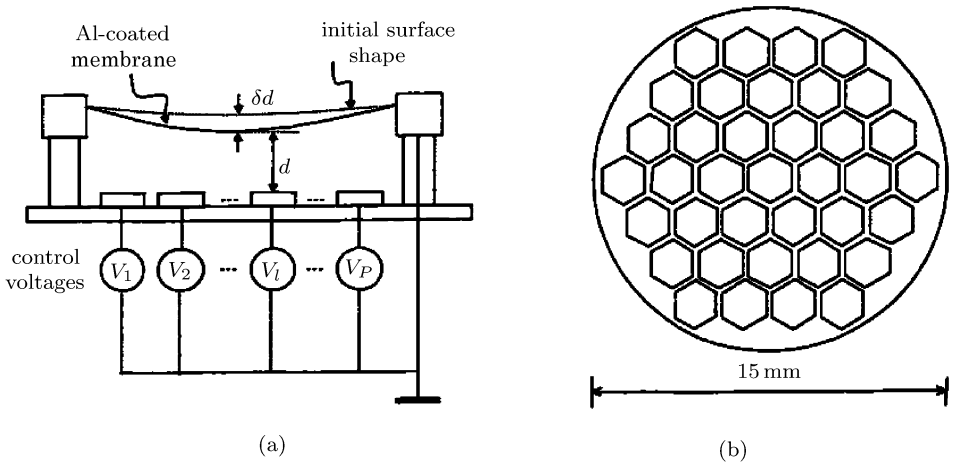


Fig.2. Schematic diagram of the MEMS DM (a) and the layout of 37 electrodes in the MEMS DM (b).

The surface properties of the deformable mirror can be created in Code V with the user-defined surface (UDS). The UDS is created in a subroutine, which is coded in C language that is supported and tested in Code V.[6] The user can define any surface that can be described by an equation $F(x, y, z)$=0, where z is the sag of the deformable mirror.

Experimentally, it is considered that the Gaussian functional form represents the DM influence function quite well. The Gaussian functional form is shown as follows:

$$Z(r) = \exp(-\beta r^2) \tag{2}$$

where β=2.77, r denotes the separation between the membrane and the electrode.[7]

If each actuator is considered to be independent, then the total deflection of the mirror can be regarded as a linear superposition of the deflections resulting from all the control channels. So the sag of the deformable mirror can be defined as

$$S(x, y) = \sum_{i=1}^{N} A_i Z_i(x, y) \tag{3}$$

where A_i is the peak deviation of the deformable mirror due to the control signal of the corresponding channel, and it is also the coefficient of the sag for the deformable mirror, and N is the total number of the electrodes. The algorithm of the UDS surface is edited according to formula (3).

3. The baseline conformal optical system

It is necessary to define a baseline conformal dome and imaging system to test the proposed correction considerations. An ellipsoidal conformal dome with equal thickness is used in this design, so the fineness ratio and the conic constant of the inner and outer surfaces are equal. The imaging system is a two-mirror all reflective system, including a parabolic primary mirror and a flat secondary mirror. The specific parameters of the baseline conformal dome are listed in Table 1.

Table 1. Parameters in the baseline dome.

Parameters	Value	Parameters	Value
dome fineness ratio $F_R(L/D)$	1.0	inner surface length, L_1	92
outer surface diameter, D_0	100	inner surface base radius, R_1	23
outer surface length, L_0	100	dome surface conic constant, k	–0.75
outer surface base radius R_0	25	dome thickness, t	4
Inner surface diameter, D_1	92	dome material	MgF2

The F/1.16 two- mirror imaging system is positioned within the baseline conformal dome. The diameter of primary mirror is 42 mm with an obscuration of about 35%. The 15 mm diameter, 37-channel MEMS deformable mirror is used in the secondary mirror. The vertex of the primary mirror is located at 60 mm

behind the inner surface of the dome. The centre of rotation is located at the primary mirror vertex. The design wavelength is 4.0 μm, and 7 zoom positions are distributed at the FOR angles from 0° to 30° in 5° increments. The full FOV is 0.6°. The final baseline system utilized throughout this study is indicated in Fig.3.

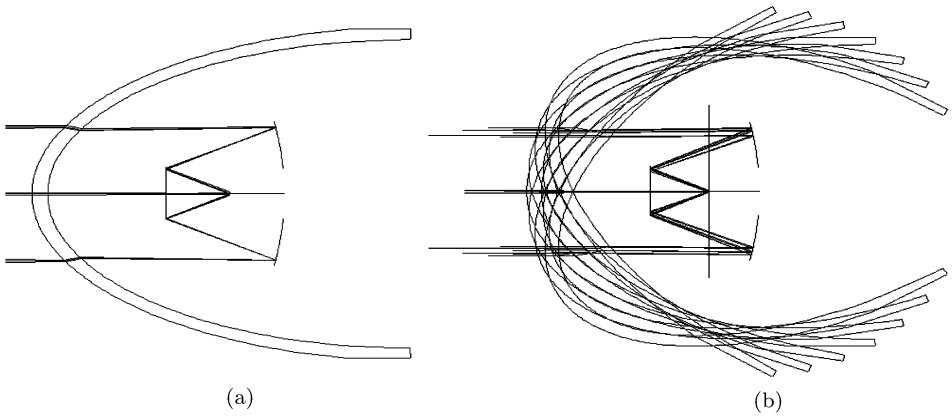


Fig.3. The layouts of the baseline conformal system for FOR angle 0° (a) and for all 7 zoom positions (b).

To overview the initial performance and better understand the dome aberrations, the first sixteen Zernike polynomials are used to represent the wavefront aberrations.[8] The curves for large amplitude aberration versus the FOR angle are plotted in Fig.4.

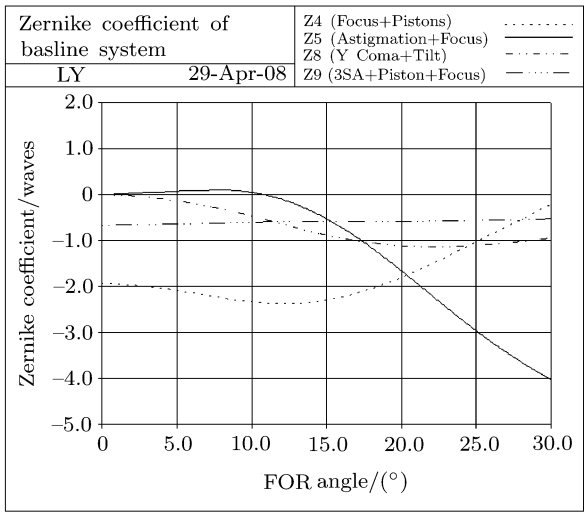


Fig.4. Curves for severe Zernike aberration versus FOR angle of the baseline conformal dome systems.

The predominated aberrations in this system are approximately 4 waves of astigmatism and 2 waves of defocus. It is evident that the conformal dome introduces many types of aberrations with significant magnitude, and each varies to some degree with respect to the FOR.

4. Corrections and optimization

The combination of the static corrector and the dynamic corrector is used in this study. Considering that the dynamic corrector which actually is a deformable mirror has a limited correction range, the static correction should be used in a conformal system to bring the aberrations down to a level that the deformable mirror can control.

4.1. Optimizing the inner surface of the conformal dome

Given a limited volume required by a missile dome, the inner surface of the conformal dome is changed into a Zernike polynomial surface which serves as a static corrector. It is no need to add other fixed correctors to achieve this. Using the default merit function in Code V and targeting the selected Zernike aberrations, after optimizing the inner surface, the peak to valley of the astigmatism can reduce from 4 waves in the baseline system to approximately 1.4 waves in the optimized dome. See Fig.5.

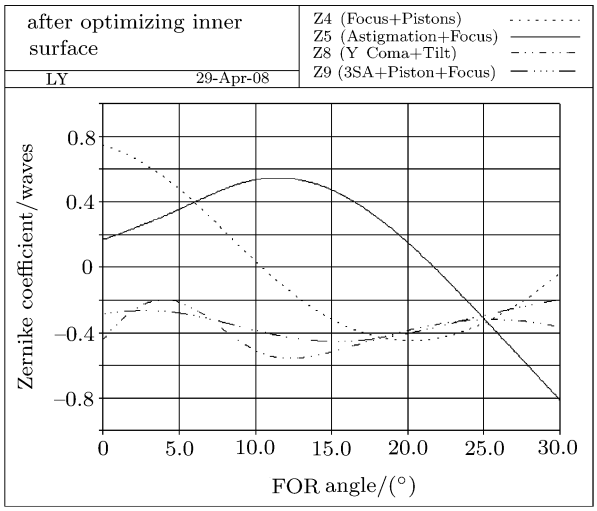


Fig.5. Zernike aberrations for the conformal dome with its inner surface optimized.

Optimization of the inner surface of the conformal dome results in the improvement on imagery, but the geometric spot size is still 7 times the diffraction limited spot size, see Fig.6. Therefore additional correction is required. Since the aberration varies with FOR angle, a dynamic correction technique must be introduced.

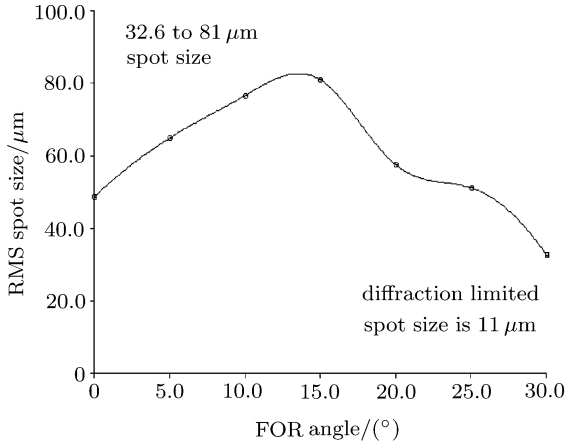
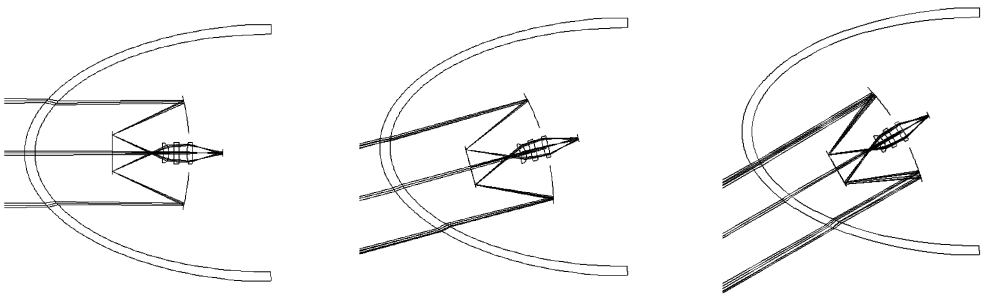


Fig.6. RMS spot size for the conformal dome with the optimization of its inner surface.

4.2. Dynamic correction by using a deformable mirror

In dynamic correction, the secondary mirror of the two-mirror imaging system is replaced by the deformable mirror. The surface of the deformable mirror is created in a subroutine called DM coded in C language, and a valid DLL file named DM.dll is produced by using the Visual Studio. net 2003. Code V can search for the DM.dll automatically according to the UMR command directory. The coefficients of 1–37 terms which represent its control voltages are varied at 7 zoom positions. So at different zoom positions, the deformable mirror has different surface profiles. The surface varies with the FOR.

The layout of the final corrected system is shown in Fig.7. The peaks to valleys of the sever Zernike aberrations are all reduced to a range from –0.4 waves to + 0.3 waves (refer to Fig.8). The curves for RMS spot size versus look angle are plotted in Fig.9. The top line shows the system spot size for the baseline conformal system without any correction. The next line shows the decrease in spot size with the inner surface optimized. The bottom line shows the RMS spot size with the combination of the static correction and the dynamic correction. For comparison, the RMS spot size of the final corrected system is reduced to 10.9–16.3 μm, which is approximately 0.99 to 1.48 times the diffraction limit. The performance of the system with combination of the static correction and the dynamic correction is very good.



(a) 0° FOR (b) 15° FOR (c) 30° FOR

Fig.7. Layouts of the final system with the combination of static and dynamic corrections.

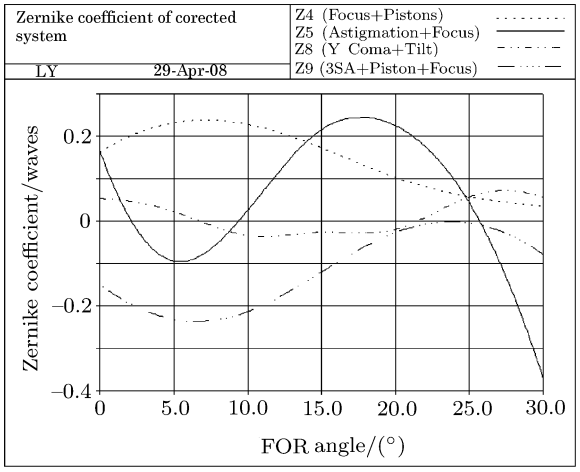


Fig.8. Zernike aberrations of the final corrected system.

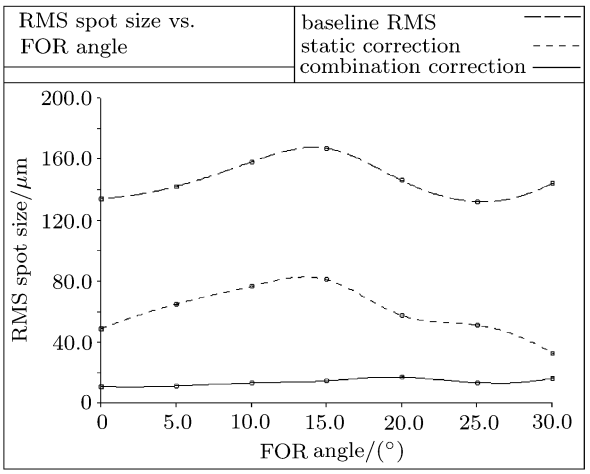


Fig.9. Comparison among the RMS spot size of the baseline system, static correction system and the final system with the combination.

5. Conclusions

Design of the combination of the static correction and the dynamic correction for a specified conformal dome is accomplished. On the one hand, it is important to optimize the inner surface of the dome, which is regarded as the static correction, and on the other hand, introducing an MEMS DM into the secondary mirror in the imaging system and optimizing it at multi-configurations can be seen as the dynamic correction.

The conformal optical system with corrections of this kind provides a small package without adding any extra corrector which is adapted to the working conditions in the missiles. A comparison between the plots of Zernike aberrations and the curves for the RMS spot size versus the FOR angle shows that the combination of the static correction and the dynamic correction is effective in conformal optical system design.

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