Vol 18 No 7, July 2009
1674-1056/2009/18(07)/2769-05

Chinese Physics B

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Correcting dynamic residual aberrations of conformal optical systems using AO technology*

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(Received 10 December 2008; revised manuscript received 23 December 2008)

This paper analyses the dynamic residual aberrations of a conformal optical system and introduces adaptive optics (AO) correction technology to this system. The image sharpening AO system is chosen as the correction scheme. Communication between MATLAB and Code V is established via ActiveX technique in computer simulation. The SPGD algorithm is operated at seven zoom positions to calculate the optimized surface shape of the deformable mirror. After comparison of performance of the corrected system with the baseline system, AO technology is proved to be a good way of correcting the dynamic residual aberration in conformal optical design.

Keywords: conformal optical design, dynamic residual aberration, SPGD algorithm, micro-electro-mechanical systems, deformable mirror

PACC: 4215E

1. Introduction

Conformal optical domes that are shaped to meet aerodynamic requirements can increase the range and speed of a missile. The outer surface of the conformal domes typically deviates greatly from spherical surface descriptions, so a variety of aberrations are induced which vary with the different field of regard (FOR).[1] Up to now, many optical correction solutions have been researched in conformal optical design, including static aberration corrections and dynamic aberration corrections.

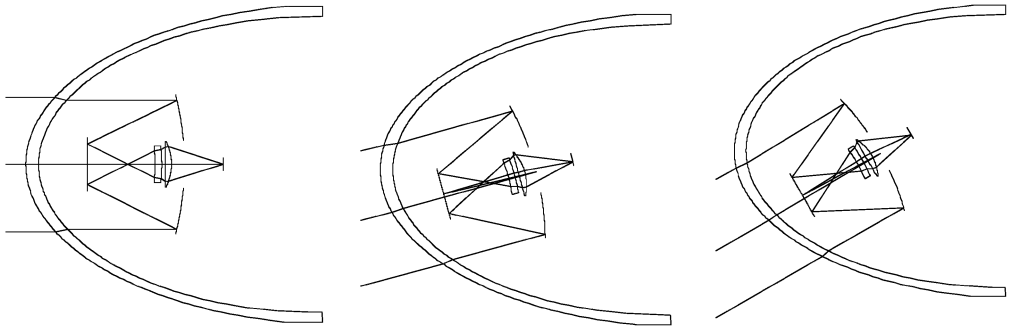
While the range of initial dynamic aberration is great, more than one correcting solutions or complicated correctors are often adopted to improve the imaging performance. Although the aberrations can be corrected to make the imaging near to diffraction-limited performance in these ways, the complication of the system is also increased. Since the missile dome has a limited space, a lightweight imaging system of simple structure is required in conformal optical design.

If one or two simple correctors are inserted into a conformal optical system, the dynamic wavefront aberrations could only be corrected approximately within two waves peak to valley in conventional conformal optical design.[2,3] But the dynamic residual aberrations still had a very bad effect on the image quality, which makes the system incapable of providing diffractive limited imagery. In order to adapt the missile to a rigorous working environment, the accuracy of infrared imaging guidance must be higher. So the adaptive optics (AO) technology is put forward as a superb solution, which can not only keep the configuration of the whole conformal optical systems simple, but can also dynamically correct wavefront aberrations.

2. Dynamic residual aberrations in baseline system

A baseline conformal system contains an elliptical conformal dome and an imaging system with a two-mirror all-reflective system, including a parabolic primary mirror and a flat secondary mirror behind the dome. In order to make the imaging system scan 30° full FOR, the system should be designed with seven zoom positions across the full FOR angles from 0° to 30° in 5° increments. Figure 1 shows the system layout at three zoom positions. The design wavelength is 4 μm.

*Project supported by the National High Technology Research and Development Program of China (Grant No 2006AA012339).
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(a) 0° FOR (b) 15° FOR (c) 30° FOR

Fig.1. Layout of a baseline system at three zoom positions.

In this system, the inner surface of the conformal dome is optimized to minimize the dynamic range of initial wavefront aberrations. In order to correct astigmatism which is the most severe aberration type, two cylinder-spherical elements are inserted behind the secondary mirror. An x-cylinder surface and a y-cylinder surface belong to the two elements respectively, which can provide variable astigmatism when the two elements are axially translated.[4]

After the optimizations are performed simultaneously over all defined zoom positions, the root mean square (RMS) spot radius versus the FOR angle is shown in Fig.2. Compared to the system before it is corrected, the RMS spot radius is clearly minimized; however, the residual RMS spot radius is still approximately 1.16∼3.87 times larger than the diffraction-limited spot radius. So it is necessary to correct these dynamic residual aberrations to make the system provide near diffraction-limited performance.

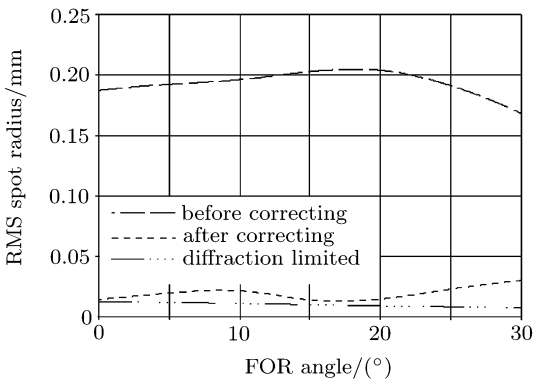


Fig.2. RMS spot radius versus FOR angle.

3. Theories of AO technology in dynamic aberration correction

AO is a technology used to improve the performance of optical systems by dynamic wavefront correction. Figure 3 shows that if a deformable mirror (DM) is placed in the secondary mirror, then the conformal system can be seen as an AO system. The DM is based on the concept of using a deformable reflective surface that is manipulated by an actuator driver which reshapes the wavefront following the instructions sent from the controller with the optimization algorithm after the incoming wavefront has been analysed by the image sensor. The actuators apply force to a specific part of the mirror's surface, resulting in the generation of complex shapes which can correct the residual aberrations present in the wavefront.

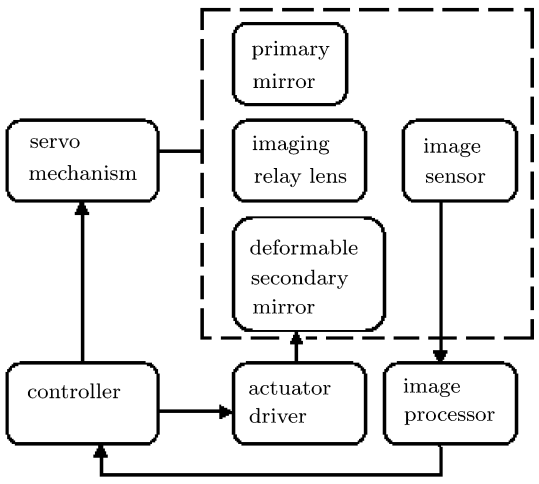


Fig.3. Block diagram of the working mode for the AO system.

3.1. MEMS DM

MEMS DM is a newly developed device based on silicon micromachining technology with the advantages of compactness and low cost.[5] A 15 mm diameter, 37-channel micro-electro-mechanical systems (MEMS) DM is used in this study. Figure 4 shows its actuator arrangement.

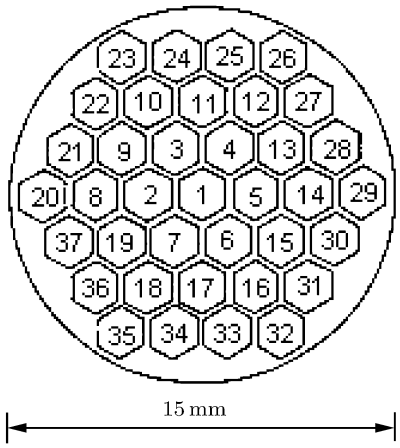


Fig.4. Actuator arrangement of the 37-element DM.

3.2. Stochastic parallel gradient descent (SPGD) optimization algorithm

Among optimization algorithms in the literature, the SPGD algorithm is the most promising for AO applications.[6] Its speed of operation can be improved by a factor of at least $\sqrt{N}$ over traditional sequential optimization techniques, where N is the dimension of the control elements of the DM. The SPGD technique can be well suited to mixed-mode very large scale integration (VLSI) implementation.

In the SPGD algorithm, a merit function $J(u)$ must be defined firstly, where $u = \{u_1, \ldots, u_i, \ldots, u_{37}\}$ are the control parameters for 37 actuators of the MEMS DM. The imaging quality is reflected by the merit function. When $J(u)$ achieves an extreme value by iteration routine, the imaging quality becomes the best. The extremal solution u is acquired by this algorithm in the last iteration cycle.

In each iteration cycle, a random ensemble of perturbations $\Delta u = \{\Delta u_1, \ldots \Delta u_i, \ldots \Delta u_{37}\}$ is applied to all 37 control parameters simultaneously, and the control voltage vector is calculated by the following equation:

$$u^{(k)} = u^{(k-1)} + \gamma \Delta u^{(k)} \Delta J^{(k)}. \tag{1}$$

The variation of the merit function in this iteration cycle is as follows:

$$\Delta J^{(k)} = J_+^{(k)} - J^{(k-1)}, \tag{2}$$

where k stands for the times of the iteration cycle, and γ is gain factor of the iteration. If the merit function is computed to the maximum, γ is positive, otherwise γ is negative. $J_+^{(k)}$ denotes the merit function after the perturbations are applied in the iteration cycle of k, and $J^{(k-1)}$ denotes the merit function before the perturbations are applied.

$$J_+^{(k)} = J[u^{(k-1)} + \Delta u^{(k)}], \tag{3}$$

$$J^{(k-1)} = J[u^{(k-1)}]. \tag{4}$$

Before each iteration cycle, the original state of the system is restored. After each perturbation, the parameter u_i is searched to adapt in a direction that increases/decreases the merit function. When Δu_i is Bernoulli distributed, the merit function has a good convergence to its extreme value after a number of iteration cycles. Figure 5 gives a schematic representation of SPGD optimization algorithm.

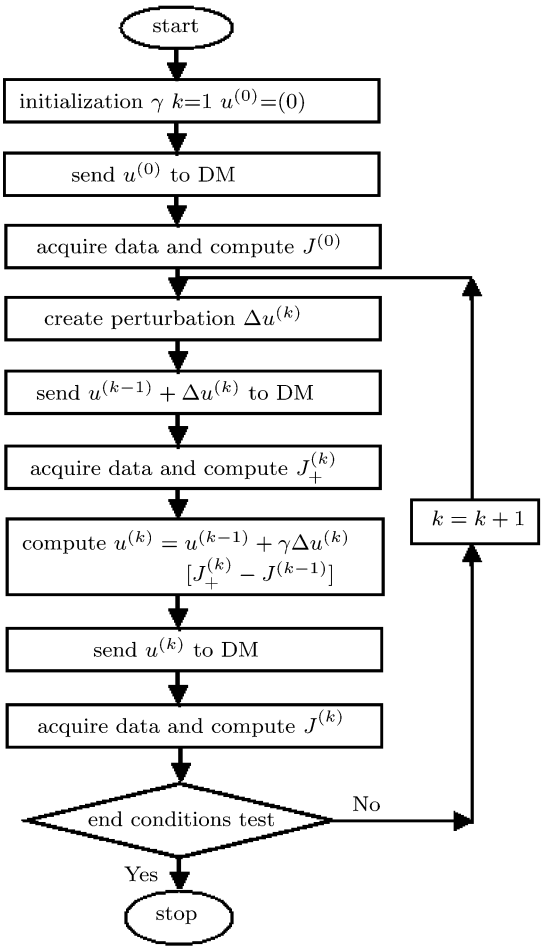


Fig.5. Schematic representation of the SPGD optimization algorithm.

4. Simulations and optimizations

The surface properties of the MEMS DM can be created in Code V with the user-defined surface (UDS). The UDS file named "DM.c" is programmed in C language according to the Gaussian function,[7] and then the file is translated into the "DM.dll" by Visual Studio software. Code V can search for the DM.dll automatically according to the UMR command. The front 37 coefficients of the surface type correspond to the control parameters for 37 actuators of the MEMS DM.

The merit function in this simulation is the sum of all the elements in a product matrix which is multiplied by two 128×128 matrices, including the SR (Strehl Ratio) matrix and a normalized matrix. The SR matrix is analysed by Code V command, and the normalized matrix has the following properties: the four corner elements are all 1; the four centre elements are all 0; the other elements are the normalized values which are varied from 0 to 1 along the centre to the corner.

When the wavefront aberration is severe, the intensity is dispersive in the image plane; at this time the merit function has a large value. Therefore the image quality is best when the merit function achieves the minimum value, so γ here is negative.

The SPGD algorithm is programmed in MATLAB, and an AO system is modeled in Code V. Communication between MATLAB and Code V is established via an ActiveX technique based on the Windows component object model (COM).[8] In each iteration cycle, MATLAB computes the control parameters $u = \{u_1, \ldots, u_i, \ldots, u_{37}\}$ and sends them to Code V; Code V alters the shape of the DM according to the received control parameters, and calculates the intensity distribution in the form of SR matrix, which is then sent back to MATLAB. This iteration goes on and on, until the termination condition is satisfied. The communication between MATLAB and Code V is shown in Fig.6. The two programs have the relationship of a server and a client.

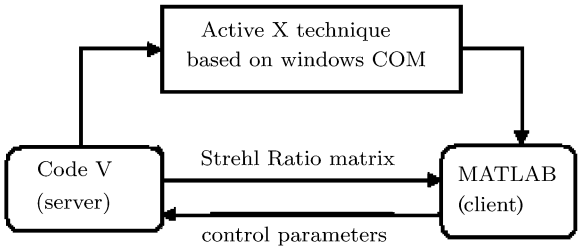


Fig.6. Communications between Code V and MATLAB.

After the SPGD algorithm has been operated at seven zoom positions, the curves for the RMS spot radius for the corrected system versus FOR angle are shown in Fig.7, and are approximately 0.53–1.41 times the diffraction-limited spot radius. Figure 8 shows that the dynamic residual wave aberrations are approximately 0.89–2.12 waves peak to valley for the baseline system, which are reduced to 0.27–1.03 waves peak to valley (PV) for the corrected system.

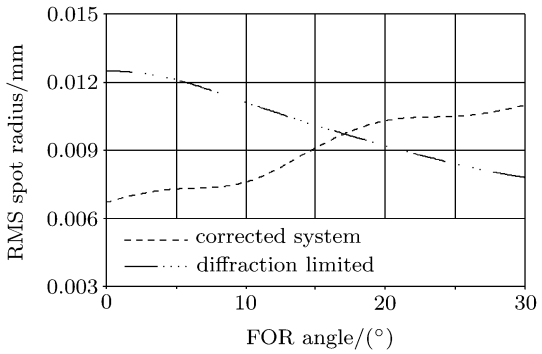


Fig.7. RMS spot radius versus FOR angle for corrected system and diffraction-limited system.

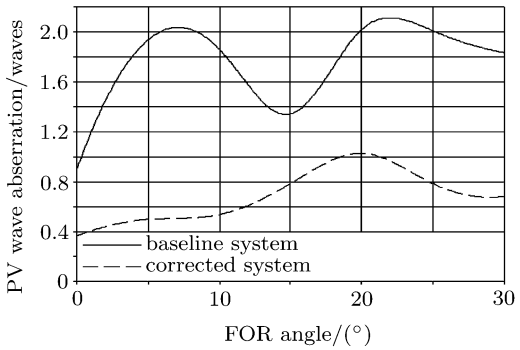


Fig.8. The PV wave aberrations versus FOR angle for the baseline system and corrected system.

The surface sag plots of MEMS DM at three zoom positions are shown in Fig.9. Considering that MEMS DM has a limited correction range, we find that the correction ability of the DM should be examined. Before the dynamic residual aberrations are corrected, the optical system at zoom 7 of 30° FOR angle has the worst imaging quality (refer to Fig.2.).

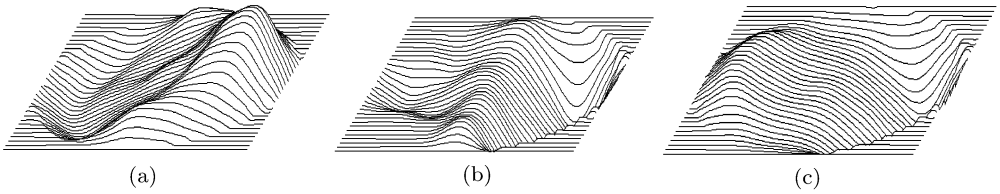


Fig.9. Surface sag plot of MEMS DM at three zoom positions: (a) zoom 2; (b) zoom 5; (c) zoom 7.

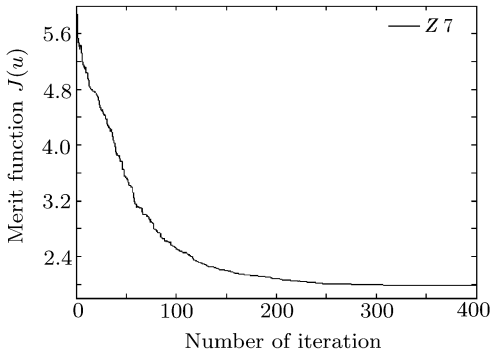


Fig.10. Convergent curves of merit function versus number of iteration for zoom 7.

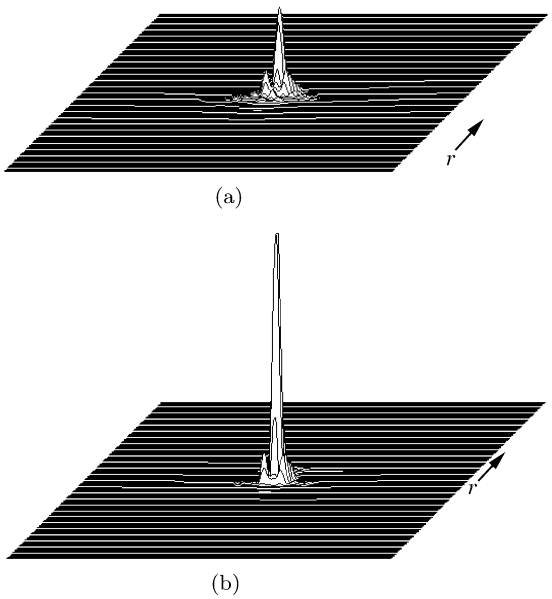


Fig.11. Plot of intensity distribution of the system for zoom 7: (a) before the residual aberrations are corrected; (b) after the residual aberrations are corrected.

Figure 10 shows the curves for the merit function varied with iteration number plotted by MATLAB at zoom 7. When the total iteration number is 400, the merit function is well convergent to a minimum value. The SR plots of the imaging wavefront for the system at zoom 7 plotted by Code V are shown in Fig.11. Compared to the system before the residual aberrations are corrected, the SR value is increased from 0.38 to 0.72. Therefore the correction capability of the AO technology with the MEMS DM is confirmed at the other zoom positions. As the system works at mid-infrared wavelength, this image quality is fine.

5. Conclusions

In conclusion, using the image sharpening AO technology is a good way of correcting dynamic residual aberrations in conformal optical design. The SPGD algorithm is operable conveniently, and the computing speed is high. The MEMS DM is used as a wavefront corrector which can simplify the optical system and reduce the cost of the whole system. In simulation, Code V and MATLAB are successful in data communication. The optimization results show that the image quality of the conformal optical system is further improved, so that the infrared imaging guidance for the missile is more accurate.

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