Combinational-deformable-mirror adaptive optics system for compensation of high-order modes of wavefront

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A new kind of adaptive optics (AO) system, in which several low spatial frequency deformable mirrors (DMs) with optical conjugation relationship are combined to correct high-order aberrations, is proposed. The phase compensation principle and the control method of the combinational AO system are introduced. The numerical simulations for the AO system with two 60-element DMs are presented. The results indicate that the combinational DM in the AO system can correct different aberrations effectively as one single DM with more actuators, and there is no change of control method. This technique can be applied to a large telescope AO system to improve the spatial compensation capability for wavefront by using current DM.

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The conventional adaptive optics (AO) system usually uses a single deformable mirror or other phase correction device to compensate for phase distortion. The compensation performance of the AO system largely depends on the characteristics of the deformable mirror (DM) and is limited by the stroke and the spatial frequency of the actuators[1]. DMs are complex opto-electro-mechanical devices. Expensive materials, strict tolerances and tough requirements to the parameters such as speed, linearity, thermal stability, temporal stability, etc., make them expensive[2]. Each kind of DM has its limits. Continuous surface DM with discrete axial piezoelectric (PZT) or electrostrictive (PMN) actuators is used widely, but the cost is very high. Both bimorph and membrane mirrors are suitable for correction of low-order aberrations in a wide frequency spectrum. Unfortunately, limited curvature of the mirror surface limits the number of control channels. Liquid crystal correctors have low-cost potentials and a great deal of elements, but their serious drawbacks such as polarization sensitivity, slow response, strong dispersion, and limited temperature range, confine their applications. Micro-electro-mechanical system (MEMS) mirrors are small, inexpensive, have very fast response and can be mass-produced. This technology has a very good compatibility with electronics, allowing for higher degrees of integration. But the drawbacks include small size (many applications require large apertures), limited range of available coatings, inferior surface quality, and difficulties of high-voltage control on a micro-scale.

Based on the characteristic of every technology, continuous surface DM with discrete actuators (PZT or PMN) is the best choice for applications to the astronomy commonly. We know that the actuator amount of DM in AO system is in direct proportional to the square of the ratio of the primary mirror's diameter to the atmospheric coherence length. The primary mirror's diameter of current telescope becomes larger and larger, so the actuator number is increasing rapidly. For example, for a 50-m telescope the DM will have about 4000 actuators (for the K-band). Because the property of material is limited, the actuator density cannot be increased limitlessly, the scale of DM must be increased accordingly. For controlling the cost and keeping the quality of DM, the manufacturing techniques to realize one DM with so many actuators is very difficult.

AO systems with double DMs, which compensate for amplitude and phase fluctuations, have received a great deal of attention[3−5]. A scheme using double DMs to prevent the instability of thermal blooming phase correction has been studied[6], and a double-DM AO system that corrected the turbulence and the scintillation has been discussed[7]. Two DMs, one whose stroke is large and the other whose spatial frequency is high, were also proposed[1]. The optical configuration that amplifies the usable stroke of a DM by arranging the wavefront to traverse the DM more than once has been demonstrated[8].

We propose a combinational deformable mirror (CDM) AO system for wavefront correction. A simple optical configuration can improve the spatial phase correction capability of the DMs on which adaptive optics depends. Several DMs are combined by $4f$ optical system in space; and the number of actuators and the coupling coefficient will be increased. Every DM has the same characteristics with low spatial frequency, and no special wavefront error is distributed in each of them for compensation. They will be equivalent to one single DM with more actuators. This design can avoid making one single large-scale DM with more actuators for the same performance.

Figure 1 shows the configuration of the spatial combination of two DMs. The $4f$ optical system that consists of lenses or mirrors is used to keep the conjugation relationship between DM1 and DM2. With the same structure, three or more DMs could be assembled, and they all will be optically conjugated to the telescope pupil in the whole AO system. This is required so that when the

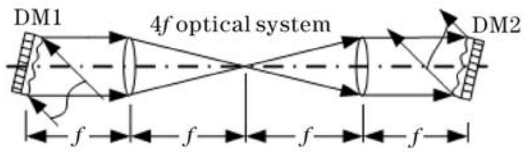

Fig. 1. Optical design of combinational DM.

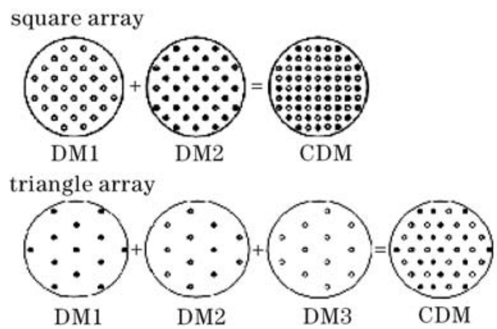

Fig. 2. Spatial configuration of CDM.

tip-tilt mirror translates the focal plane spot, it will not cause the pupil image to move.

The important factor in this system is the configuration of the relative spatial location of the actuators belonging to different DMs. The location will be intercrossed and form a new array. To keep the symmetry, different numbers of DMs are needed in different arrays. Generally, two DMs are necessary for the square array, and three DMs are necessary for the triangle array, as shown in Fig. 2. Thus the combinational arrays will remain the same actuator pattern, but the density augments. All the actuators with new adjacent relationships combine into a new equivalent DM in the optical system.

Generally, the surface displacement of a DM can be expressed as[9]

$$M(x,y)=\sum_{i=1}^{N}A_i f_i(x,y), \tag{1}$$

where A_i is the voltage signal applied to the ith actuator, and $f_i(x,y)$ is the actuator influence function.

Based on the principle of linear system, the surface displacement of CDM M_{C} can be expressed as

$$M_{\mathrm{C}}(x,y)=M_1(x,y)+M_2(x,y)+\cdots+M_n(x,y), \tag{2}$$

where M_n is the displacement of the nth DM.

For the continuous surface piezoelectric mirrors, which have been used widely, the influence function can be written approximately as[10]

$$f_i(x,y)=\exp\left[\ln(\omega)\left(\frac{\sqrt{(x-x_i)^2+(y-y_i)^2}}{d_0}\right)^{\alpha}\right], \tag{3}$$

where ω is the coupling coefficient, (x_i,y_i) is the center coordinate of the ith actuator, d_0 is the interval between the adjacent actuators, and α is the Gaussian index.

So for the combination of two DMs with the square array and the same influence function, when the available numbers of actuators are N_1 and N_2 respectively, and the interval of the combination d becomes $\frac{\sqrt{2}}{2}d_0$, we can get the surface displacement from Eq. (2) as

$$\begin{aligned}M_{\mathrm{c}}(x,y)&=\sum_{j=1}^{N_1}A_j f_j(x,y)+\sum_{k=1}^{N_2}A_k f_k(x,y)\\&=\sum_{j=1}^{N_1}A_j\exp\left[\ln(\omega)\left(\frac{\sqrt{(x-x_j)^2+(y-y_j)^2}}{d_0}\right)^{\alpha}\right]\\&\quad+\sum_{k=1}^{N_2}A_k\exp\left[\ln(\omega)\left(\frac{\sqrt{(x-x_k)^2+(y-y_k)^2}}{d_0}\right)^{\alpha}\right]\\&=\sum_{n=1}^{N_1+N_2}A_n\exp\left[\ln(\omega)\left(\frac{\sqrt{(x-x_n)^2+(y-y_n)^2}}{d_0}\right)^{\alpha}\right]\\&=\sum_{n=1}^{N_1+N_2}A_n\exp\left[\ln(\omega^{2^{-\frac{\alpha}{2}}})\left(\frac{\sqrt{(x-x_n)^2+(y-y_n)^2}}{d}\right)^{\alpha}\right].\end{aligned} \tag{4}$$

We define $\omega^{2^{-\frac{\alpha}{2}}}$ as pseudo-coupling coefficient; the result indicates that the combinational DM is equal to one single DM with N_1+N_2 actuators, the coupling coefficient $\omega^{2^{-\frac{\alpha}{2}}}$, and the same Gaussian index α.

Analogously, for the combination of three DMs with the triangle array, the surface displacement of CDM can be expressed as

$$\begin{aligned}M_{\mathrm{c}}(x,y)&=\sum_{n=1}^{N_1+N_2+N_3}A_n\\&\quad\times\exp\left[\ln(\omega^{3^{-\frac{\alpha}{2}}})\left(\frac{\sqrt{(x-x_n)^2+(y-y_n)^2}}{d}\right)^{\alpha}\right].\end{aligned} \tag{5}$$

Thus the wavefront compensation elements of the AO system would be increased. This method can be also applied to the DM combination with other arrays.

A close-loop CDM AO system with two DMs is shown in Fig. 3. The CDM can be controlled in the same way as one single DM, because the surface displacement will be expressed as Eq. (4) or (5). The direct-gradient wavefront control algorithm that is widely applied in practical AO systems is used here. In this method, the relationship between the control voltage V of the actuators (that is, for DM1 and DM2) and gradient vector G measured by

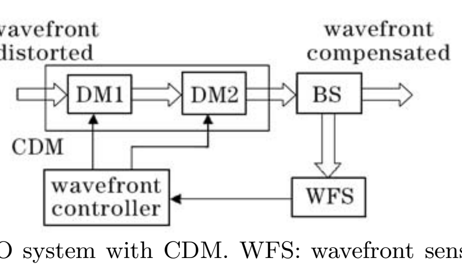

Fig. 3. AO system with CDM. WFS: wavefront sensor; BS: beam splitter.

WFS can be written as[11]

$$V = R^{+}G, \tag{6}$$

where R is the gradient response matrix from DM to Hartmann-Shack wavefront sensor (WFS), R^{+} is the pseudoinverse of matrix R.

From the above analysis, we can conclude that there is no change to conventional control method of DM in the CDM AO system, and it does not increase the complexity of system when improving the spatial frequency that can be compensated.

A numerical simulation model is set up for a two-DM system, each DM has 60 available actuators. In Fig. 4, DM1 is rotated by $\pi/4$ and DM2 is rotated by $-\pi/4$, then they will be staggered, the dashed circle that implies the inscribed circle of actuators is the CDM's available region for wavefront correction. So the CDM will have 120 actuators. Because aberrations can be expressed by Zernike polynomials or by Karhunen-Loeve (K-L) polynomials[12], which are orthogonal on a unit circle, we suppose the aberration to be corrected is expressed by the first 35 order Zernike polynomials. We define the fitting coefficient as

$$\beta_{\mathrm{recon}-j} = \sqrt{\iint (Z_j(x,y) - M(x,y))^2 \mathrm{d}x\mathrm{d}y} \Bigg/ \sqrt{\iint Z_j^2(x,y)\mathrm{d}x\mathrm{d}y}, \tag{7}$$

where Z_j is the jth Zernike wavefront, M calculated in the least square arithmetic is the wavefront compensated by DM. Suppose the coupling coefficient is 5%, the Gaussian index is 2.6, the interval between the adjacent actuators on one of the DMs is 0.257 on a unit circle. Calculating from Eqs. (4) and (7), the correction performances of this CDM and the single 60-actuator DM are compared. The result is shown in Fig. 5. It is clear that the compensation capability of CDM is much better than one single DM with 60 actuators. The enhancement is mainly due to the increase of actuator number and the coupling coefficient of the CDM. More analyses indicate that the CDM does not introduce more errors for low-order aberrations compared with one single DM with the same actuator number; and the CDM has more valid stroke than the single DM, too. According to Harvey[9] increasing the coupling coefficient may profit correcting low-order aberrations. So the CDM is a good scheme for improving the spatial capability of wavefront compensation.

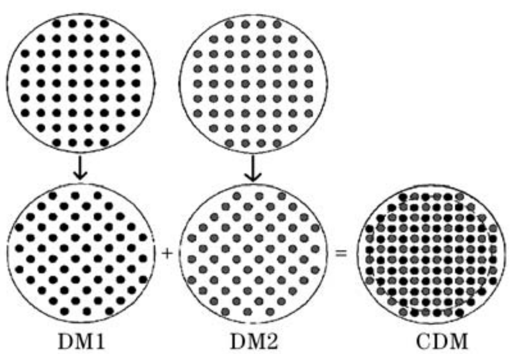

Fig. 4. Spatial configuration of a numerical model.

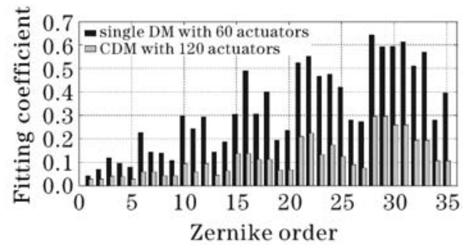

Fig. 5. Fitting coefficients of CDM and single DM.

In summary, we have presented a design by which several DMs are combined in one AO system for wavefront correction. The formula of CDM's surface displacement has been demonstrated. The numerical simulation has validated that the CDM can enhance the spatial frequency and wavefront correction capability of phase compensation. Thus, the CDM AO system can improve wavefront correction capability without increasing cost of manufacture and control. This scheme can be used easily in the large telescope AO system and other situations for correction of complex aberrations.

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