Experimental verification of combinational-deformable-mirror for phase correction

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In adaptive optics (AO) system, the phase compensation capability is limited greatly by the actuator number of the deformable mirror (DM). The actuator number of DM is mainly restricted by the manufacture techniques. The spatial correction capability of AO system can be improved by two or more combinational-DMs (CDMs) with conjugation relationship. The CDM AO system for wavefront correction is built, which consists of two 32-element DMs. The experimental results are in agreement with the numerical simulation results. It is indicated that the CDM AO system provides better correction performance than the single 32-element DM AO system.

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The conventional adaptive optics (AO) system usually uses one phase correction device to compensate for phase distortion. The compensation performance of an AO system largely depends on the characteristics of the phase correction device and is limited by the number of the deformable mirror (DM) actuators.

Liquid crystal spatial light modulator (LC-SLM)[1−3] and micro-electro-mechanical systems (MEMS) DMs[4,5] can integrate a great deal of actuators, but they have many drawbacks which limit the areas of possible applications[6]. The drawbacks of LC-SLM include polarization sensitivity, slow response, strong dispersion, limited temperature range, and so on. The disadvantages of MEMS mirror include insufficient stroke, too small size elements, scattering, difficulties with multilayer coating, and difficulties of high-voltage control on a micro-scale. The continuous face-sheet DM with discrete actuators[7] is still a good solution to modern astronomical AO problems for its advantages, such as freedom from stroke limitations, suitable scale, and sophisticated manufacture techniques. Nevertheless, it is also difficult to integrate too many actuators.

Combinational-deformable-mirror (CDM) comprised of two or more DMs with conjugation relationship can be used to improve the spatial correction capability of an AO system and decrease the actuator number of single DM. The actuators of DM in CDM should be staggered to keep the symmetry of CDM's actuator array. Different numbers of the DMs are needed for different arraies. Generally, two DMs are needed for the square array, and three DMs for the triangle array, which are shown in Fig. 1. All the DMs of CDM must be optically conjugated to the telescope pupil in the astronomical AO system. Under that condition, when the tip-tilt mirror translates the focal plane spot, the pupil image does not move. Double-DM AO system was proposed by Hu *et al.*[8], in which two DMs have different characteristics, and special wavefront error is distributed to each of them for compensating. In CDM AO system, all the DMs have same characteristics including actuator arrangement, actuator spacing etc., and no special wavefront error is distributed to each of them. Because the surface displacement of the CDM equals the summation of all DMs' and the surface displacement of single DM is equivalent to the linear weighted superposition of actuator influence functions[9], the surface displacement of CDM can be expressed as the linear weighted superposition of all DMs' actuator influence functions. That is, the activity of CDM can be regarded as a single DM, so the direct-gradient wavefront control algorithm[10,11] can be employed to control the CDM. In this letter, we experimentally study a CDM AO system for phase correction to verify its feasibility.

The experimental setup is shown in Fig. 2. The light source is an expanded 632.8-nm collimated light beam and DM1 is close to DM2, so it is not necessary to keep the conjugation relationship between DM1 and DM2 with additional optical system. Phase aberration element which is a piece of low-quality glass in our experiment is used to provide distorted wavefront. The Shack-Hartmann wavefront sensor (SHWS) has 30 × 30 sub-apertures, and its measure precision is 0.1λ (peak valley value) and 0.05λ (root mean square). The digital

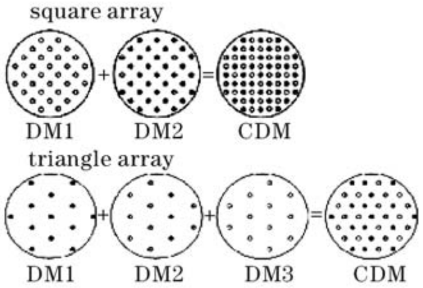

Fig. 1. Actuator arrangement of CDM.

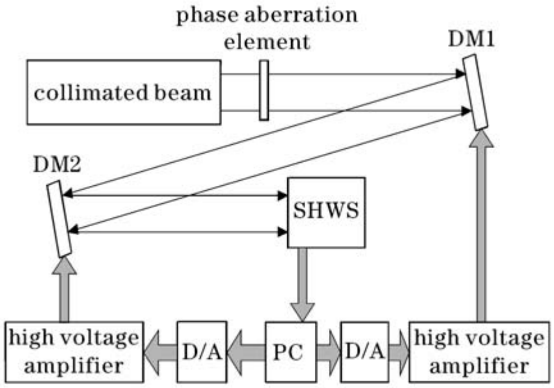

Fig. 2. Experimental setup.

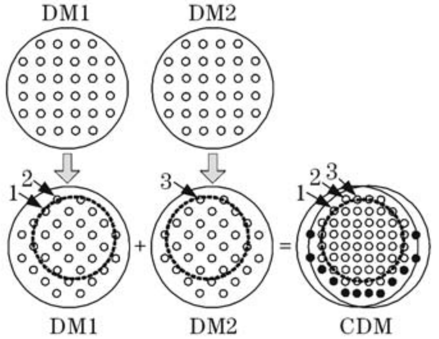

Fig. 3. Actuator configuration of DM1, DM2, and CDM.

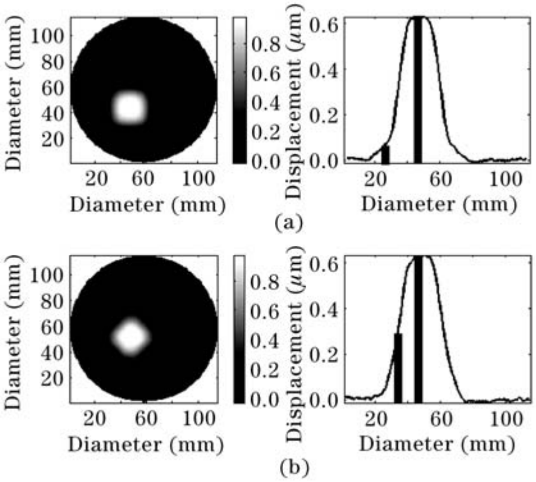

Fig. 4. Tested influence functions of (a) DM1 and (b) CDM.

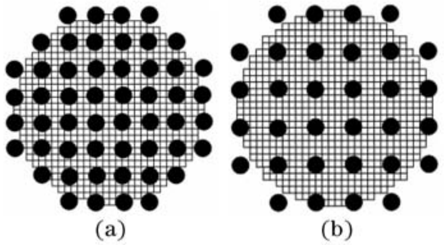

Fig. 5. Configurations of sub-apertures (squares) and actuators (filled circles) of (a) CDM AO system and (b) single 32-element DM AO system.

to analog convertor (D/A) is a high-density analog voltage output card. Its voltage output is 10 V and differential linearity error is 0.001% within the full-scale range. The voltage gain of high voltage amplifier is 100.

The most important factor in this system is the actuators configuration of CDM (see Fig. 3). Two DMs (DM1 and DM2) have the same actuator number (32), same actuator arrangement (square), and same actuator spacing (23 mm). Both of them are rotated by $\pi/4$ and then staggered to make the actuator arrangement of CDM square. In order to keep the symmetry of actuator array, the actuators indicated by filled circles are not used, so only 52 actuators are available in this system. The dashed circle implying the common part of two DMs is the CDM's available region for wavefront correction, whose diameter is 110 mm.

According to Fig. 3, the adjacent relationship of actuators has changed. For example, the adjacent actuator of actuator 2 is actuator 1 on DM1 while actuator 3 on CDM, so the actuator spacing of CDM becomes $\sqrt{2}/2$ times of that of DM1 and DM2. Because adjacent actuators are not on a single DM in the CDM, the coupling between adjacent actuators of CDM is different from the coupling of single DM. Here, we define it as pseudo-coupling. As a result of reduction of actuator spacing, the pseudo-coupling is larger than the coupling of DM1 and DM2. The influence functions of DM1, DM2 and CDM have been tested using ZYGO interferometer[12], as shown in Fig. 4. Because DM1 and DM2 are rotated by $\pi/4$ when they are employed to construct the CDM, the shape of CDM's influence function is rotated by $\pi/4$ compared with DM1's influence function. The coupling values of DM1 and DM2 are about 5%, and the pseudo-coupling value of CDM is about 30%.

To compare the wavefront compensation capability of CDM, a 32 channels AO system was also constructed by using the DM1 alone. The available region of the DM1 is also 110 mm. The configurations of HSWS sub-apertures (squares) and actuators (filled circles) of the two AO systems are shown in Fig. 5.

Based on direct-gradient wavefront control algorithm, several groups of close-loop correction experiments were carried out. Here we present the results for three phase aberration elements (No. 1, No. 2, No. 3). The original wavefront aberrations without correction and residual wavefront errors close-loop corrected by the DM1 and by the CDM are all shown in Fig. 6. The far field images of close-loop correction obtained from the SHWS are shown in Fig. 7.

The compensation capability of the CDM AO system is much better than that of the single 32-element DM AO system. The enhancement of compensation capability is mainly due to the increase of CDM's actuator number and coupling value.

According to Ref. [13], if the distorted wavefront and the DM's influence functions are known, the minimum residual wavefront can be obtained by least square algorithm, which implies the theoretical optimal correction of the DM to the distorted wavefront. Based on the influence functions shown in Fig. 4 and the original phase aberrations shown in Fig. 6, the CDM's and DM1's optimal corrections to each of the three phase aberration elements are calculated. The comparison of experimental

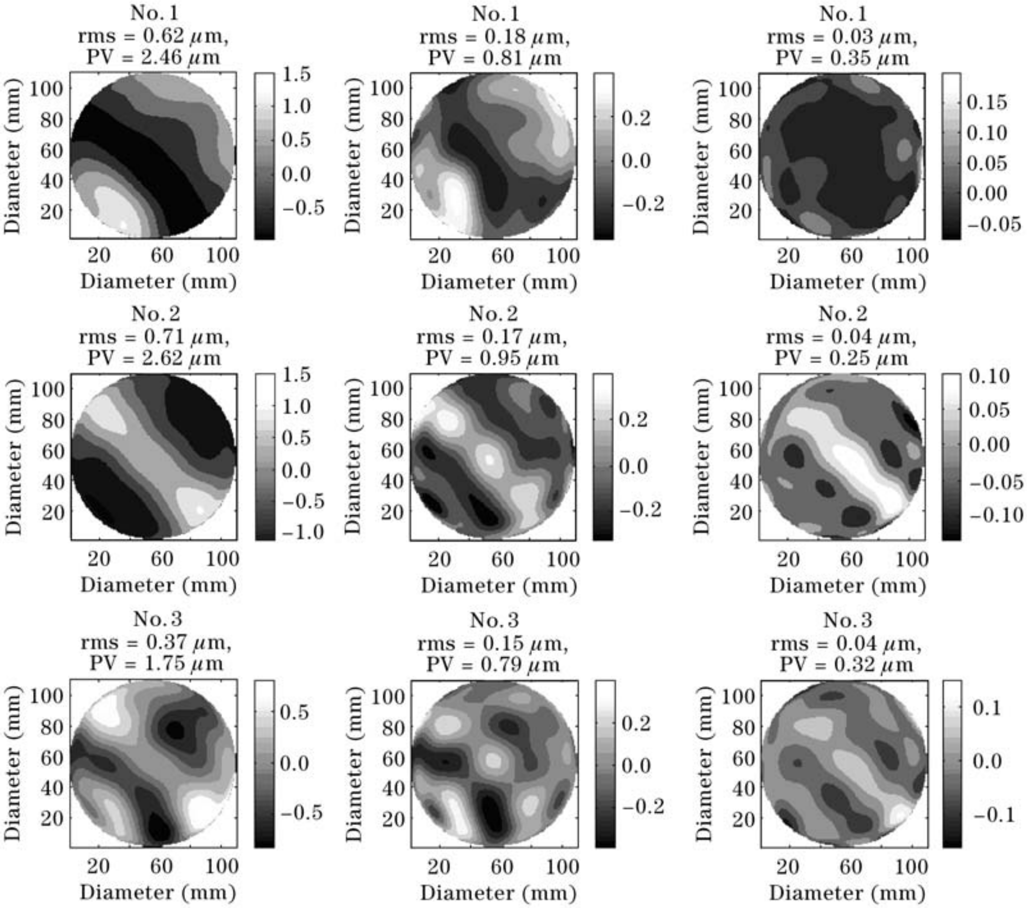

Fig. 6. Experimental results of wavefront aberrations: from left to right is original wavefront without correction, with single 32-elmemt DM close-loop correction, and with CDM close-loop correction.

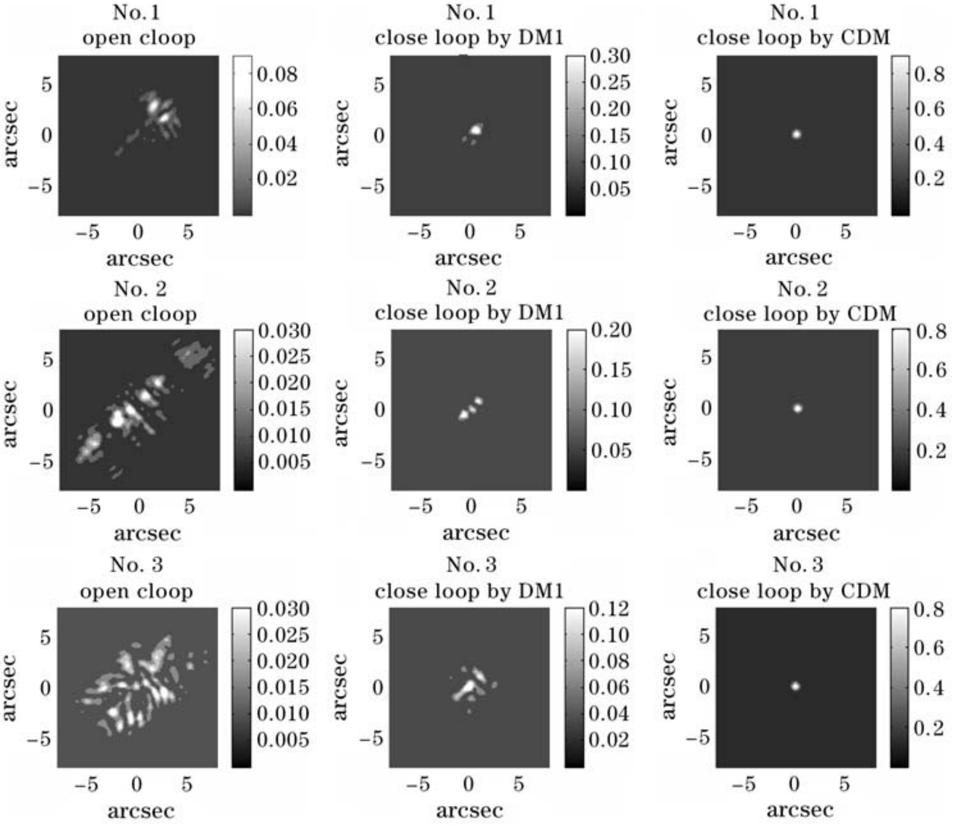

Fig. 7. Experimental far field images.

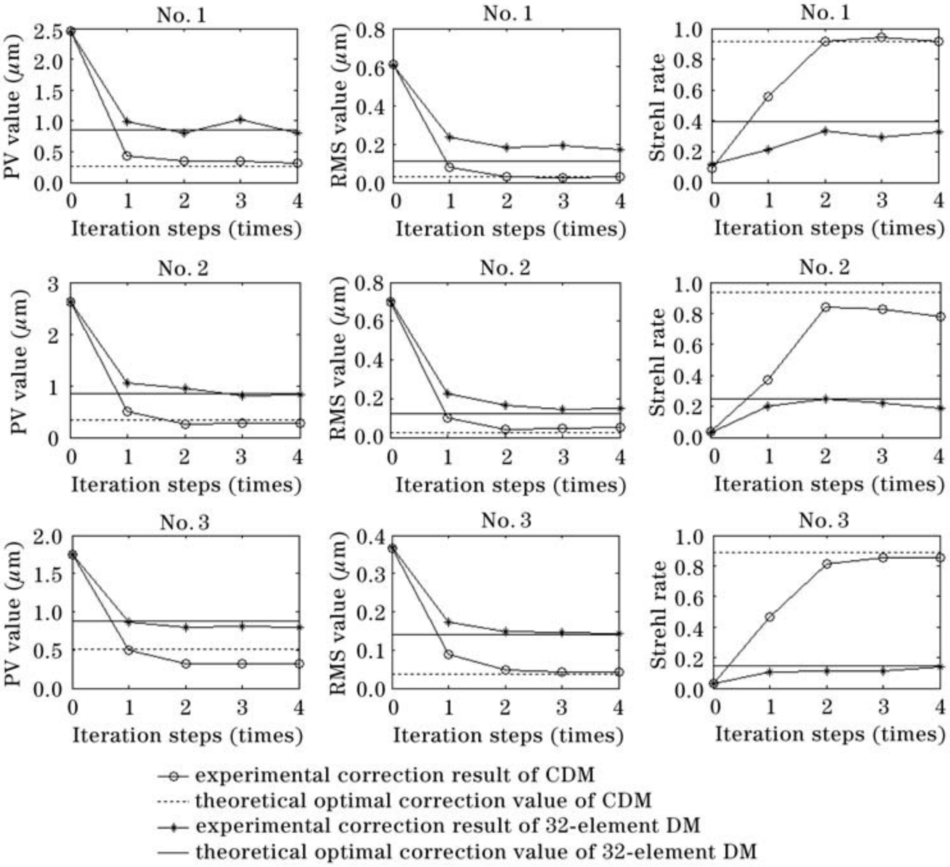

Fig. 8. Comparison of experimental results and theoretical optimal correction results.

results and theoretical optimal correction results is shown in Fig. 8. From it, we can see that the experimental results are in agreement with the theoretical optimal correction values, so the phase correction principle of CDM has been verified.

In conclusion, the enhanced phase compensation performance of the CDM AO system was validated by close-loop correcting the distorted wavefront induced by different phase aberration elements. Based on the experimental results and theoretical calculations, we can increase the actuator number of the phase correction device and enhance wavefront compensation capability of the AO system by using the CDM. Compared with one DM with many actuators, the CDM can be realized much easier to increase actuator density of phase correction device. Especially, in telescope AO system, the actuator number of DM is directly proportional to the square of primary mirror's diameter, we can use CDM to increase the actuator density and reduce the fabrication difficulty of single DM.

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