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A Circular Bimorph Deformable Mirror for Circular/Annulus/Square Laser Beam Compensation

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We are studying the application of an adaptive optics system to upgrade the beam quality of a laser. The adaptive optics (AO) system consists of a bimorph deformable mirror, a Shack-Hartmann sensor and a control system. In most AO applications, the beam aperture is considered to be circular. However, in some cases such as laser beams from unstable resonators, the beam apertures are annulus or a holed-rectangle. In this paper, we investigate how well a bimorph deformable mirror of ϕ120 mm clear aperture can compensate phase distortions for three different beam configurations; 1) ϕ120 mm circular aperture, 2) ϕ100 mm annulus aperture with a ϕ20 mm hole and 3) 70 mm $\times$ 70 mm square aperture with a hole of 30 mm $\times$ 30 mm. This study concludes that the bimorph mirror, which might be considered as a modal controller, can compensate tilt, defocus, coma and astigmatism, and spherical aberration for all three beams.

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I. INTRODUCTION

Systems of adaptive optics (AO) remove the wavefront distortion caused by a turbulent medium by introducing a controllable counter wavefront distortion that spatially and temporally follows the distortion of the atmosphere [1]. An adaptive optics has been prominently used in the astronomical community to compensate for the wavefront aberrations induced by the earth's atmosphere. Nowadays, adaptive optics has other applications such as in high-powered laser systems, ophthalmic systems, laser communications, microscopy and underwater imaging systems [2-7]. Conventional adaptive optics systems work in a closed-loop configuration in which the phase control element, such as a deformable mirror, is iteratively adjusted to null the phase residual measured by a wavefront sensor.

We are currently studying the application of an adaptive optics system to upgrade the beam quality of a laser. We consider the adaptive optics system to consist of a bimorph mirror, a Shack-Hartmann sensor [8] and a control system. Since the laser beam can be circular, annulus or square/rectangle, we predicted the performance of a circular bimorph deformable for different beam shapes. We selected a bimorph mirror of 120 mm clear aperture with 32 actuators as a design candidate.

We used computer simulation to investigate the circular bimorph mirror's fitting or compensating ability for circular/annulus beams as well as for our square beam. With the aid of commercial software for finite element analysis (FEA), we calculated the influence of various functions. We then calculated the fitting ability or compensating ability by feeding the influence functions to control signals through a conventional least-square control algorithm.

II. THE FITTING ABILITY OF THE BIMORPH MIRROR

1. Mathematical Framework: Residual Errors & Fitting Ability

For an incoming wavefront distortion $\phi(r,\theta)$ over a circular aperture of arbitrary radius R, the deformable mirror (DM) generates its approximate conjugate $\hat{\phi}(r,\theta)$ in order to minimize the residual fitting error e^2 as given by

$$\hat{\phi}(R\rho,\theta) = \sum_{i=1}^{m} a_i r_i(\rho,\theta) \quad (1)$$

$$e^2 = \iint [\phi - \hat{\phi}]^2 W(\rho)\rho d\rho d\theta \quad (2)$$

where

$$\rho = r/R \quad (3)$$

a_i is the command to the i^{th} actuator
r_i is the influence function of the i^{th} actuator

$$W(\rho) = \begin{cases} 1/\pi, & \rho \le 1 \\ 0, & \rho > 1 \end{cases}$$

Suppose we sample the DM surface at n surface points $\vec{x}_j$, $j = 1,\cdots,n$, with normalized sampling distant $S = \Delta x/R$, then the relationship between the surface position and the actuator command can be described in matrix notation as

$$\hat{\phi} = Ha \quad (4)$$

In the above, the n dimensional vector $\hat{\phi} = [\hat{\phi}(\vec{x}_1), \cdots, \hat{\phi}(\vec{x}_n)]^T$ represents the discrete corrected phase profile. The $n \times m$ DM configuration matrix H, whose i^{th} column is the vector $[r_1(\vec{x}_1),\cdots,r_i(\vec{x}_n)]^T$, is independent of time. Then the actuator control signal $a_i(t)$ and the residual error e^2 would be as follows:

$$a(t) = (H^T H)^{-1} H^T \phi(t) \quad (5)$$

$$e^2 = \frac{1}{n} S^2 \phi^T P \phi \quad (6)$$

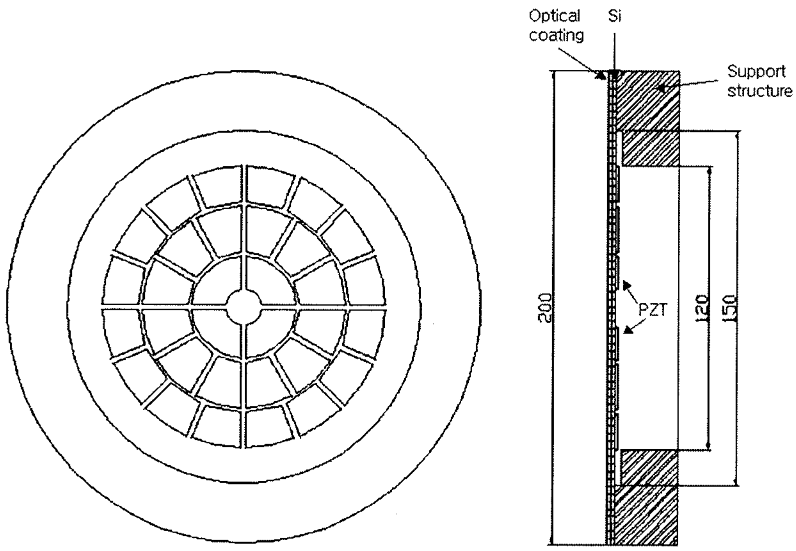
where $P = (I - H(H^T H)^{-1} H^T)^T (I - H(H^T H)^{-1} H^T)$ (7)

Here we can also define 'Fitting Ability' (FA) as follows. The fitting ability can be interpreted as (1 - normalized RMS wavefront error). It becomes one for a perfect match for the incoming wavefront and zero vice versa. This fitting ability explains how well the mirror matches the given wavefront errors.

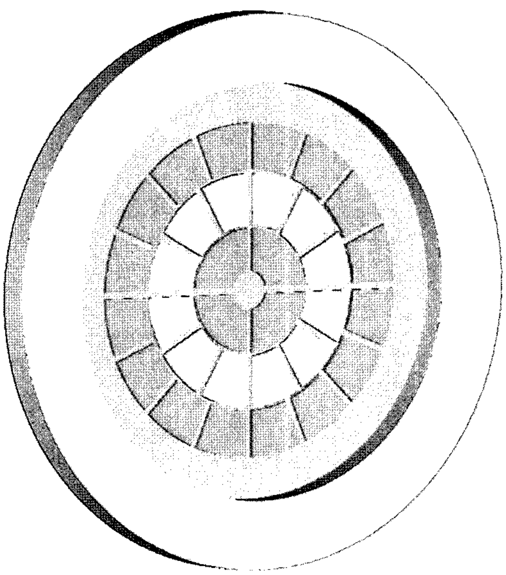
$$FA = 1 - Normalized\_wavefornt\_error = 1 - \frac{\int [\phi - \hat{\phi}]^2 W(\rho)\rho d\rho \int d\theta}{\int [\phi]^2 W(\rho)\rho d\rho \int d\theta} \quad (8)$$

2. Mirror model & influence functions

For our adaptive optics system, we selected as the deformable mirror a bimorph mirror with 32 actuators. Fig. 1 shows the schematic drawings of the DM and a model used in the FEA software. The front surface of the DM is made of single crystalline Si with a thickness of 3 mm, and the mirror is coated for reflection. The DM has a clear aperture of 120 mm and was edge-mounted by a support structure with a diameter of 150 mm. To allow for deflection at the edge of clear aperture, there is 30 mm between the edge of the third-ringed actuators and the mounted structure. We used FEA software to calculate the influence functions [10]. Table 1 summarizes the FEA results.



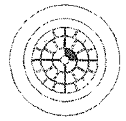
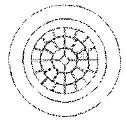
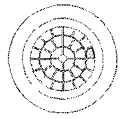
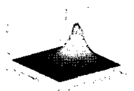
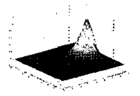
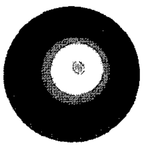
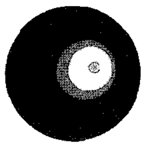
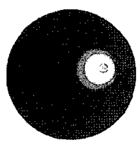
(a) Schematic drawing



(b) A model in FEA software

FIG. 1. Schematic drawing of the DM and its model in FEA software.

TABLE 1. Influence functions of the bimorph mirror.

	1st ring	2nd ring	3rd ring
Pattern			
Influence function			
Contoured influence function			

3. Fitting ability for a circular or annular beam

The bimorph mirror can be figured in order to minimize the residual wavefront errors. The control signals or the optimum shapes of the bimorph mirror for various aberrations can be derived as described in the previous section with the assumption of a perfect and instant wavefront sensing and instant wavefront correction.

Fig. 2 shows the best fitting mirror shapes for some low-order Zernike polynomials (such as the tilt, defocus, coma, astigmatism and the spherical aberration) in accordance with Noll's definition [9]. We set the diameter of the entrance pupil of the incoming wavefront to 120 mm, which is the outer diameter of the third ring actuators.

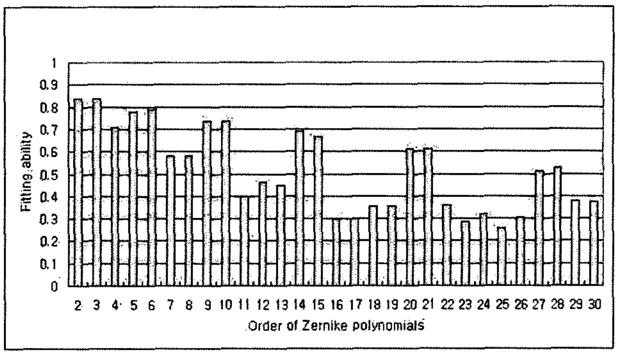
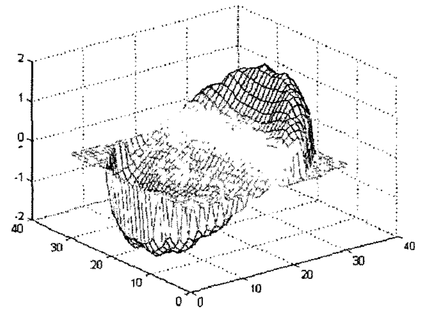


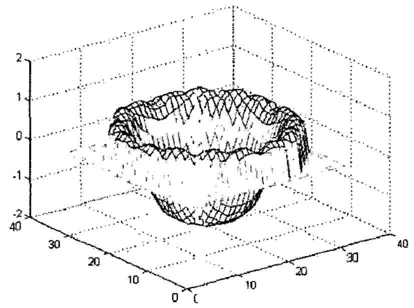
FIG. 3. DM's fitting ability for the Zernike polynomials.

Fig. 3 shows the mirror's fitting ability. Fig. 2 and Fig. 3 show that the performance is degraded by the edge effects of the third ring actuators and the absence of a center actuation.

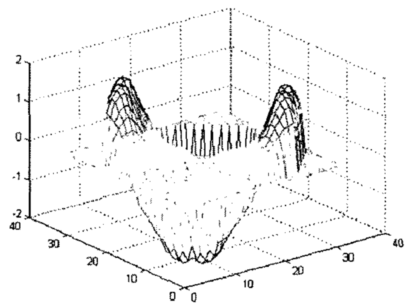
Fig. 4 shows the contoured influence functions of all the actuators together. From this figure, it is intuitively clear that the performance of the DM would improve if we removed the edge effects and the effect of the absence of a central actuator by limiting the effective aperture of the DM. For the limited DM area, we chose an outer diameter of 100 mm and an inner diameter of 20 mm. Fig. 5 shows the fitting ability of the bimorph mirror of this case. The bimorph mirror can compensate the lower Zernike polynomials with a fitting ability larger than 0.95 for low-order aberrations.



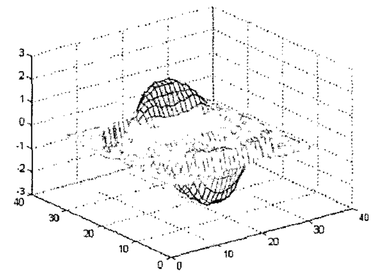
(a) Tilt



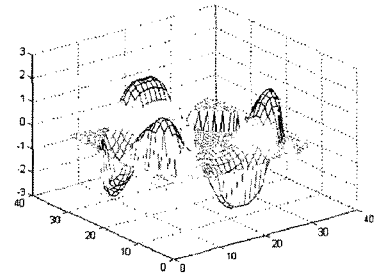
(b) Defocus



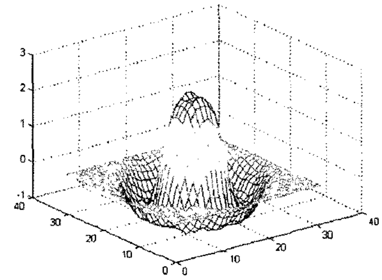
(c) Coma



(d) Astigmatism

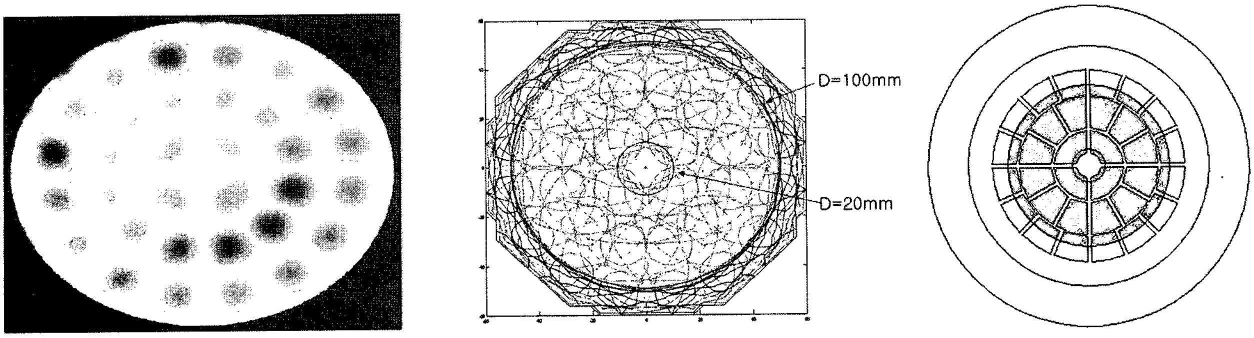


(e) Trefoil



(f) Spherical aberration

FIG. 2. DM's optimal fitting shapes for some low-order aberrations.



(a) Contoured influence functions of all actuators (b) Limited effective area for the bimorph mirror

FIG. 4. Contoured influence functions of all actuators and the limited effective area for the bimorph mirror.

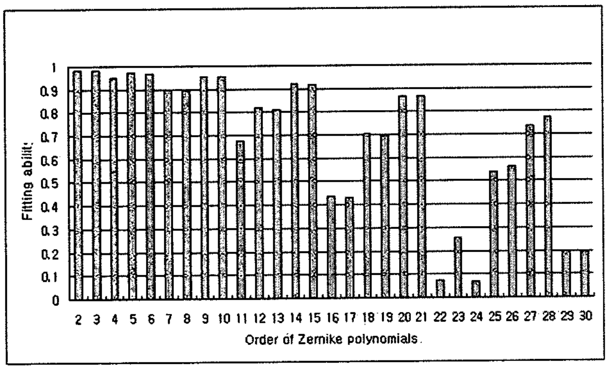


FIG. 5. DM's fitting ability for the Zernike polynomials when the incoming wavefront is an annulus with an outer diameter of 100 mm and am inner diameter of 20 mm.

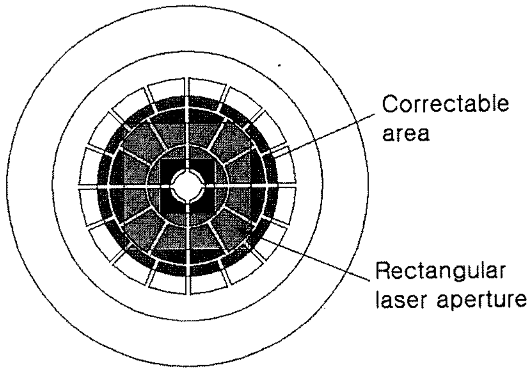


FIG. 6. Correctable area of the bimorph mirror with the aperture of the square laser beam.

4. Fitting ability of the square beam

We now select a square beam that fits into the effective or correctable area as found in section 2.2. The square beam was selected to have a square hole that might be generated by a scraper of an unstable resonator. Fig. 6 shows the correctable or limited area of the bimorph mirror, along with the aperture of our square laser beam. The square laser beam fits perfectly into the correctable area. Fig. 7 shows the fitting ability of the bimorph mirror for the square wavefront aberrations. In this calculation, we used parts of the Zernike polynomials defined only in the square beam area as the incoming wavefront aberrations. This figure shows that the bimorph mirror, which is a kind of a modal controller, can compensate the lower-order aberrations with fitting abilities larger than 0.95 for tilt, defocus, coma and astigmatism, and 0.82 for the spherical aberration.

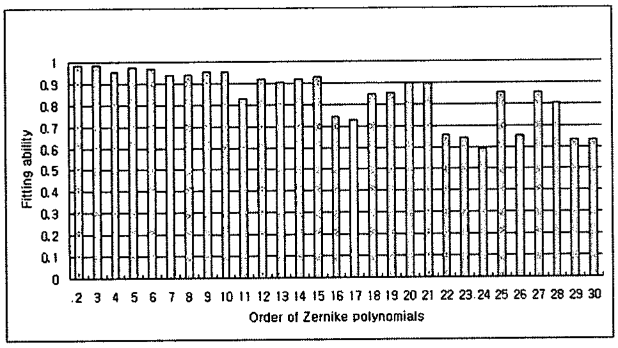


Fig. 7. DM's fitting ability for the Zernike polynomials when the incoming wavefront is a 70 mm × 70 mm square laser beam with a 30 mm × 30 mm hole.

III. CONCLUSION

We studied the use of a bimorph mirror for compensating the cavity-induced wavefront distortions of circular, annular and square laser beams. We found that a bimorph mirror of 120 mm clear aperture has an effective area of 100 mm outer diameter and 20 mm inner diameter. For a square laser beam, in spite of the initial issue of outside actuators, we concluded that the circular bimorph mirror provides excellent compensation for a square laser beam because the size of the square laser beam is smaller than the correctable area. The excellent fitting ability is largely due to the fact that a bimorph mirror is a kind of modal controller.

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