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Experimental analysis of the fitting error of diffractive liquid crystal wavefront correctors for atmospheric turbulence corrections

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ABSTRACT

An experimental analysis was conducted to investigate the fitting error of diffractive liquid crystal wavefront correctors (LCWFCs). First, an experiment was performed to validate the theoretical equations presented in our previous work Cao et al., 2009 [9]. The results showed an apparent discrepancy between the theoretical and measured results for the fitting error. This difference was examined and the influence of nonlinearities and rounding errors generated by the LCWFC was analyzed and discussed. Finally, the fitting error formula of the LCWFC was modified to obtain a more effective tool for the design of LCWFCs for atmospheric turbulence correction. These results will be useful for researchers who design liquid crystal adaptive optics systems for large-aperture ground-based telescopes.

1. Introduction

Liquid crystal adaptive optics has been widely investigated [1–4]. Although the monochromatic nature of the liquid crystal wavefront corrector (LCWFC) makes it useful only for a very restricted number of cases on large telescopes, it is still a very potential solution to correct for atmospheric turbulence in large-aperture telescopes [5–7] because of its advantages, including millions of pixels, compact size, and low price. To correct for atmospheric turbulence, the fitting error will be produced by the discrete actuators of the wavefront correctors (WFCs) as described by Hudgin [8], who has published a formula to calculate the fitting error for deformable mirrors. It must be noted, however, that we have previously demonstrated (Cao et al., 2009, [9]) that Hudgin's method is not suitable for diffractive WFCs. Normally, the kinoform method [10,11] is utilized to produce a large phase magnitude for LCWFCs. To implement the kinoform technique, the phase modulation is wrapped into 1λ and then quantified with the corresponding LC pixels. Therefore, the quantization level means the number of LC pixels needed to realize 1λ phase modulation. Because the pixel size of LCWFC is on the order of microns, the wavefront fitting error is directly determined by the quantization level without the need to consider the pixel size. Its diffracted wavefront root mean square (RMS) error is [12]:

$$\varepsilon = \frac{\lambda}{2\sqrt{3}N} \tag{1}$$

where λ is the wavelength and N is the quantization level. To calculate the fitting error of the LCWFC, the quantization level N should be calculated first. We have previously developed a formula to calculate N as follows [9]:

$$P = 6.25N + (15 - 1.5D - 23N + 0.91ND)r_0^{-5/6} \tag{2}$$

where P is the pixel number of the LCWFC along one dimension, D is the telescope aperture, and r_0 is the atmospheric coherence length. The units of D and r_0 are centimeters. Here N is defined as the minimum quantization level that meets the condition that the sum of the quantization levels larger than N should occupy 95% of the quantization levels included in the atmospheric turbulence. The quantization level N can be calculated if D, r_0, and P are constant. Then, the fitting error can be obtained with Eq. (1). In other words, when the telescope aperture and the atmospheric turbulence coherence length are known, the LCWFC can be designed by using Eqs. (1) and (2).

In our former work, the fitting error of the LCWFC is only theoretical analyzed and simulated [9]. In the paper, experimental analysis on the fitting error of the LCWFC will be performed and the actual characteristics of the LCWFC, such as the nonlinear phase modulation and the quantization step error will be considered. Firstly, the validation experiment is performed. Then, the performances of LCWFC are considered and its effects on the

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fitting error are analyzed. At last, a modified equation is given.

2. Validation experiment

2.1. Validation scheme

To validate the fitting error formulas of the LCWFC, a comparison must be performed between the theoretical and experimental fitting errors. To measure the fitting error of the LCWFC, the atmospheric turbulence wavefront ϕ (P, D, r_0) should first be calculated from Kolmogorov turbulence theory [13,14]. Then, the calculated atmospheric turbulence wavefront is sent to the LCWFC and reproduced by it. Finally, the reproduced wavefront ϕ_m (P, D, r_0) is measured. With the calculated and measured atmospheric turbulence wavefronts, the RMS value of the fitting error can be computed by:

$$\varepsilon_{\exp} = \sqrt{\left\langle \left| \phi_m(P, D, r_0) - \phi(P, D, r_0) \right|^2 \right\rangle} \tag{3}$$

where $<|\ |^2>$ denotes phase variance.

The atmospheric turbulence wavefront is described with Noll's Zernike polynomials model [13]. The first 406 modes of the Zernike polynomials are used to simulate the atmospheric turbulence wavefront. To produce the fitting wavefront with the kinoform technique, the simulated atmospheric turbulence wavefront shown in Fig. 1(a) should be wrapped into 1λ and quantified. Then, the quantified wavefront is converted to a gray map for driving the LCWFC as shown in Fig. 1(b).

A parallel-aligned LCWFC (BNS, P256) was used to produce the atmospheric turbulence wavefront with a $6.14\times6.14\ \text{mm}^2$ aperture, 256×256 pixels, and 24 μm pixel pitch. The previous calculated results [9] showed that the quantization level $N\geq8$ is suitable for the wavefront correction. Hence, this level was selected to perform the fitting error evaluation. To evaluate the fitting error of the LCWFC, different conditions were considered with the atmospheric coherence length of 10 cm and the selected parameters are shown in Table 1. Using these parameters, the theoretical fitting error ε_T can be calculated as shown in Table 1.

2.2. Optical layout

A Fizeau interferometer (ZYGO) was used to measure the reproduced wavefront of the LCWFC; its optical layout is shown in Fig. 2. The combination of lenses L1 and L2 is used to amplify the sampling area of the ZYGO interferometer. A polarizer is utilized to make the polarization direction of the light parallel to the alignment direction of the LC molecules. The collimating laser beam emitted from ZYGO interferometer passes through two lenses and a polarizer, and then it is reflected by the LCWFC. The reflected light enters the ZYGO interferometer and the reproduced wavefront of the LCWFC can then be measured.

Table 1
Selected parameters and the theoretical fitting errors.

N	P	D/r_0	D(m) (r_0=10 cm)	ε_T (λ)
8	64	6	0.6	0.0361
9	100	13	1.3	0.0321
10	128	16.9	1.69	0.0289
11	128	14.1	1.41	0.0262
12	128	11	1.1	0.0241
13	256	31	3.1	0.0222
14	256	28	2.8	0.0206

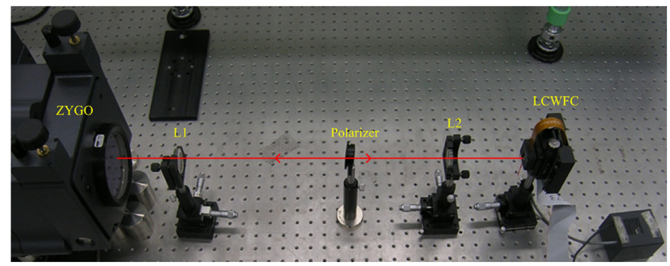

Fig. 2. Optical layout for measuring the reproduced wavefront.

2.3. Experimental result

As the atmospheric turbulence is random, 100 atmospheric turbulence wavefronts were utilized to calculate the fitting error according to Eq. (3). Before measuring the reproduction wavefront, the reference wavefront should be measured to eliminate the distortion caused by optical aberration. The fitting error formula of Eq. (3) can be rewritten as:

$$\langle \varepsilon_{\exp} \rangle = \sqrt{\left\langle \left| \phi_m - \phi_{ref} - \phi \right|^2 \right\rangle} \tag{4}$$

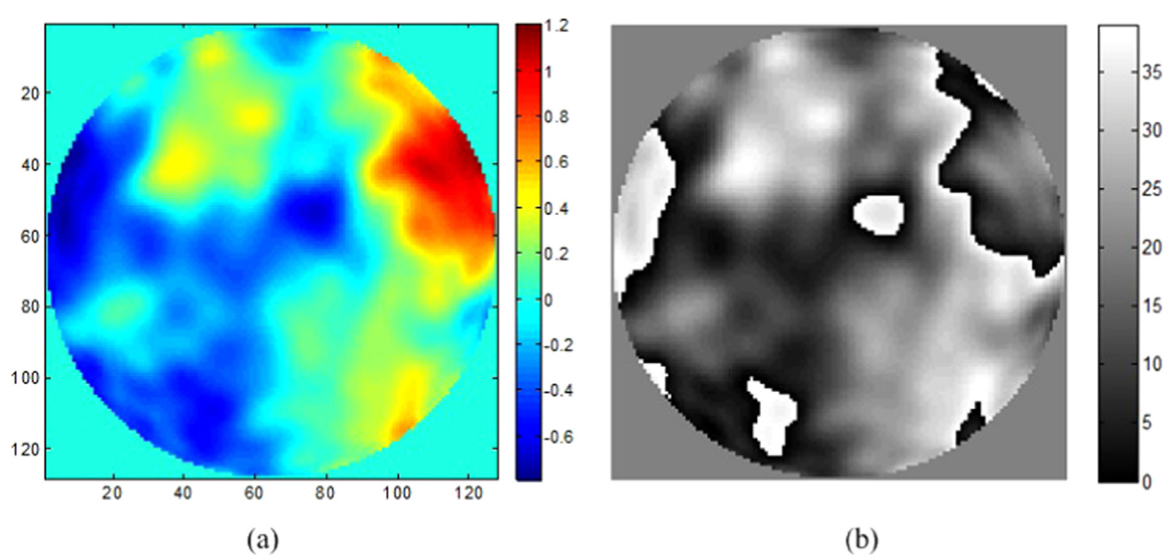

Fig. 1. Atmospheric turbulence wavefronts: (a) Simulated; (b) Gray map.