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Performance simulation of an adaptive optics system with liquid crystal corrector under closed-loop and open-loop control

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ABSTRACT

The adaptive optics system (AOS) often operates in a discrete sampling process with finite closed-loop frequency. Reconstruction, detection, and time lag induced errors are the main correction errors of the system. An AOS that is based on a liquid crystal (LC) benefits from the LC's high correction precision, thus the reconstruction error can be ignored. The primary error will be induced by the time lag from the time of detection to the time of compensation. In this paper, some theoretical simulations are introduced in order to evaluate the correction precision of AOS with an LC corrector. The main purpose is to compare the correction precision between the open-loop and closed-loop control. We attempt to find a method to ascertain the exact precision of the open-loop control and show whether it improves the correction precision. The conclusion is thus reached that the actual error rejection bandwidth for the closed-loop was lower than the −3 dB error rejection bandwidth measured in practice. The increased refresh frequency of the open-loop control can improve the imaging performance to nearly −3 dB bandwidth of the detector measured, which is the maximum possible bandwidth due to the time lag.

1. Introduction

Liquid crystal (LC) corrector has been proven to be a very high-precision corrector for generating a desired wave-front, which is beneficial for open-loop control [1–3]. So, the reconstruction error induced by the LC corrector could be ignored. The error induced by the time lag from the time of detection to the time of compensation may have a major impact on the performance of the LC corrector-based AOS for turbulence compensation.

The disturbance rejection bandwidth, defined as the frequency where half the disturbance power is rejected by the AOS, was often used to evaluate the correction precision of AOS [4]. The amplitude of an input and output disturbance signal was used to calculate this rejection efficiency. The Fourier transform procedure was used to calculate the frequency spectrum of both the residual error and the disturbance. It is convenient to define the disturbance rejection in deci-Bells (dB) via the following equation:

$$\mathrm{rej(dB)} = 20\log_{10}\left(\frac{\text{Residual error amplitude}}{\text{Input turbulence amplitude}}\right)$$

The half power rejection point is where the calculation of this equation equals −3 dB [4]. For a closed-loop system, the wave-front detector, usually a Shack Hartmann Sensor (SH-Sensor), records the amplitude of the residual error in each correction loop. This is a discrete time-varying signal. Then, the Fast Fourier Transform (FFT) algorithm was used to translate it into the frequency domain and determine its rejection bandwidth.

However, this method was unusable for an open-loop configuration, which was attempted to be used in a new generation AOS, such as in the Multi-Object AOS for making giant telescopes in the future [5]. In an open-loop configuration, the SH-Sensor was blind to the residual error [6]. Hence, the conventional method to evaluate its disturbance rejection property cannot be used. The precision evaluation was directly based on the imaging performance before and after correction, which was directly, but not quantitatively, related to the correction precision.

In this paper, some theoretical simulations were introduced to evaluate the real-time performance of AOS with an LC corrector under the closed-loop and open-loop control, respectively. Moreover, some theoretical comparisons are attempted and relationships between these two different control methods are determined for the purpose of evaluating the correction precision of an LC-based AOS under open-loop control according to its closed-loop performance.

2. System configuration and time consumption

This method was based on the real-time response of an LC corrector in AOS. Linear response was used to represent the LC

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response process. The whole correction process was established according to the actual operation sequence and time consumption. The AOS used for simulation consists of an LC on a silicon wavefront corrector and a SH-Sensor. The optical layouts for both closed-loop and open-loop control have been introduced in a previous work [6].

The time flow chart for the closed-loop and open-loop controls is shown in Fig. 1. The t_1, t_2, t_3, t_4, and t_5 represent the exposure time (2 ms), reading time (2 ms), reconstruction time (0.7 ms), transmission time (4.5 ms), and LC response time (2.6 ms), respectively. These times were matched with the actual time consumption measured for this system. The exposure and reading time were related to the SH-Sensor. The reconstruction time was used to calculate the correction signal according to the aberration the SH-Sensor detected. The transmission time was used to transmit the correction signal onto the LC head. The holding time (t_6) was the time interval between two LC responses. The LC corrector holds the previous correction signal in this period until the next correction signal transmission is complete.

3. The real-time performance simulation

Using the model established above, the real-time response of an LC corrector and SH-Sensor were simulated. A simple sinusoidal signal with 5 Hz frequency was used to simulate the turbulence signal in time domain. The sampling interval used for simulation was 0.01 ms, which means that the actual response value of the LC corrector and the SH-Sensor was simulated every 0.01 ms for an authentic description. Then, the real-time response of the LC corrector and SH-Sensor due to the model were established for closed-loop and open-loop controls. The residual error was calculated at the same time. The disturbance rejection property was calculated according to this simulation.

3.1. Closed-loop control

Under closed-loop control, all the commands worked in a serial processing mode. The latest detection must perform after the LC corrector completely generated the last correction map. The LC then held this correction signal until the next transmission was complete. The time lag for each correction loop was $\tau = t_1 + t_2 + t_3 + t_4 + t_5 = 11.8$ ms. The response and holding times for the LC corrector were 2.6 and 9.2 ms, respectively, indicating that the refresh frequency of the LC corrector was equal to the closed-loop frequency, which is nearly 84 Hz for this system. Fig. 2 illustrates this real-time correction performance. A 5 Hz sinusoidal signal with amplitude equal to one was used to simulate the disturbance. The green, red and blue lines represent the disturbance, correction, and residual error signals, respectively. The LC corrector held the correction voltage for 9.2 ms and then responded to a new voltage in 2.6 ms.

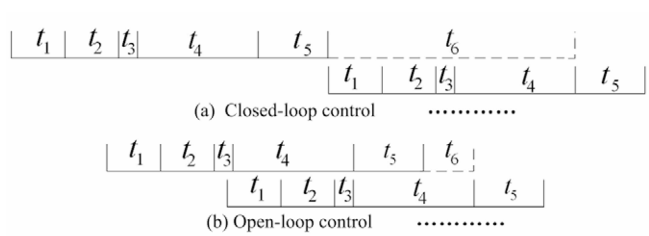

Fig. 1. The time flow chart of AOS with different control modes.

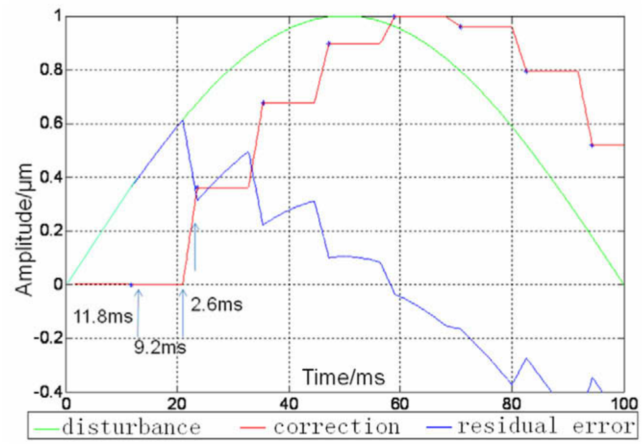

Fig. 2. Real-time performance of AOS under the closed-loop control.

3.2. Open-loop control

In the open-loop configuration, the SH-Sensor was located before the LC corrector to detect the absolute disturbance in each correction loop. It was not necessary for the SH-Sensor to wait for a complete response from the LC corrector. Some of the commands could be set into a parallel processing mode, as shown in Fig. 1b. Under this consideration, the optimal parallel configuration was therefore restricted by the longest operation in each correction loop, identified as the transmission process in this system. The refresh time for each operation could be reduced from 11.8 to 4.5 ms, equal to the transmission time t_4. The refresh frequency improved from nearly 84 Hz to over 222 Hz, which then induced the LC corrector's holding time to decrease from 9.2 to 1.9 ms. Although the time lag for each correction loop was still 11.8 ms, it meant that the one-step correction precision was the same as that of the closed-loop. The real-time response of the LC corrector, as shown in Fig. 3, was totally different. The green, red, and blue lines represent the disturbance, correction, and residual error signals, respectively. The LC corrector held the correction voltage for 1.9 ms and then responded to a new voltage in 2.6 ms. Since the time lag for each correction loop was still 11.8 ms, the first correction was always performed in 11.8 ms. Then, the refresh frequency changed to 222 Hz.

4. Precision evaluation and discussion

From the simulation above, the open-loop control was clearly found to improve the correction frequency, a benefit from the

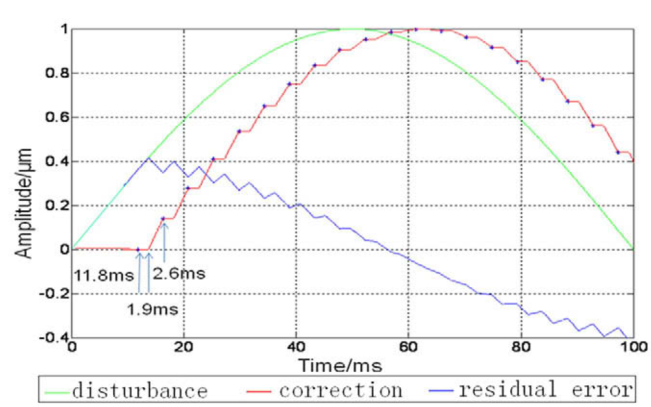

Fig. 3. Real-time performance of AOS under the open-loop control.

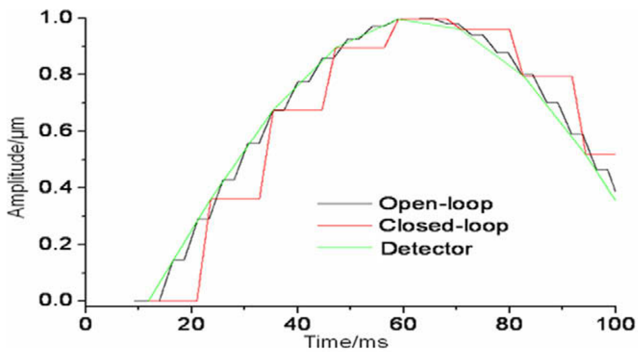

Fig. 4. Comparison of the LC response for different controls.

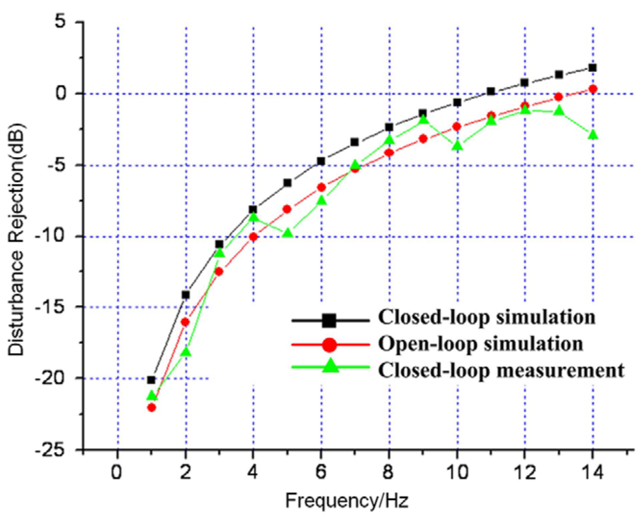

Fig. 5. The disturbance rejection property of the AOS.

optimized parallel configuration. A comparison of the real-time response of the LC corrector between closed-loop and open-loop is shown in Fig. 4. The green line represents the discrete correction signal for the closed-loop control detected by the SH-Sensor. The open-loop control improved the refresh frequency from 84 to 222 Hz, which induced the response of LC corrector smoother than in closed-loop control. Although they have the same one-step correction time lag, the open-loop control was more rapid and precise due to the increased refresh frequency. As shown in Fig. 4, the black line is closer to the green line than the red line.

Ideally, this increased refresh frequency may improve the imaging performance. To evaluate the correction precision improvement quantitatively, the real-time responses were translated into a frequency spectrum to calculate the disturbance rejection property by the Fourier transform procedure.

Simulated sinusoidal signal with a different frequency was used as the disturbance signal. Then, the detection and correction signals were calculated according to the above simulation. Using the Fourier transform procedure, the disturbance and residual error were educed and changed into a frequency spectrum. The amplitude of each spectrum was used to calculate the rejection property. Under this procedure, the disturbance rejection property for the open-loop and closed-loop control was calculated. The black and red lines in Fig. 5 represent the closed-loop and open-loop rejection properties, respectively. The green line is the rejection property measured with the SH-Sensor in the laboratory for this AOS. A tip–tilt mirror was used to generate the sinusoidal tilt signal. The time consumption was the same with simulation. The disturbance and the residual signal were recorded by the SH-Sensor in each correction loop. Then, the frequency spectrum was calculated.

The frequency spectrum indicated that the simulated real-time performance of the closed-loop control was a little worse than what was measured using the SH-Sensor in practice. The open-loop control improved the real-time performance according to the simulation. The -3 dB error rejection bandwidth was increased from 7.4 to 9.2 Hz when the system was changed into an open-loop control. In addition, this bandwidth was closer to the bandwidth measured in the laboratory. For sinusoidal signal disturbance from 1 to 14 Hz, the averaged improvement was -1.78 dB, which meant that the amplitude of the residual error for the open-loop control was 81% of the closed-loop control.

5. Conclusion

In this paper, some theoretical analyses were introduced to evaluate the performance of an LC corrector-based AOS in the closed-loop and open-loop control, respectively. The whole correction process was established according to the actual operation sequence and time consumption. From this study, we conclude that the actual imaging performance of the closed-loop control was slightly worse than the system capability measured using the SH-Sensor due to the discrete sampling property. The open-loop control benefits from the increased refresh frequency as it can raise the performance of the AOS closer to the ideal pure time delay system, which is nearly 10 Hz for the present system. The open-loop control can ideally improve the performance of an imaging system. The averaged improvement was -1.78 dB, which means that the amplitude of the residual error for the open-loop control was 81% of the closed-loop control.

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References

[1] P. Prieto, E. Fernández, S. Manzanera, P. Artal, Opt. Express 12 (2004) 4059.
[2] C.R. Vogel, Q. Yang, J. Opt. Soc. Am. A 23 (2006) 1074.
[3] G.D. Love, Appl. Opt. 36 (1997) 1517.
[4] D. Dayton, S. Browne, J. Gonglewski, SPIE 5894 (2005) 58940M.
[5] C. Blain, O. Guyon, R. Conan, C. Bradley, SPIE 7015 (2008) 701534.
[6] Q. Mu, Z. Cao, D. Li, L. Hu, L. Xuan, Appl. Opt. 47 (2008) 4297.