Improving the performance of adaptive optics system using robust compensator

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Abstract: - This paper discusses the application of a simple and tunable robust compensator for an adaptive optics system, based on the Robust Model Matching (RMM) strategies. We have made some laboratory experiments with the atmospheric simulation instruments. Simulation and experimental results shows that the system with the designed controller has improved significantly comparing with the previous work.

Key-Words: - Adaptive optics, Control system design, Robust model matching, Robustness, Attachable compensator

1 Introduction

Adaptive Optics (AO) refers to the use of deformable mirrors (DM) driven by active control loops that feedback wavefront sensor (WFS) measurement to compensate for turbulence-induced phase distortion of optical waves propagating through the atmosphere. The objective of an AO system in astronomy is to reduce, as much as possible, the effects of the distortion in real-time by adjusting the shape of a DM, in order to remove the aberration using closed loop feedback control [1, 2]. Most of the Adaptive Optics (AO) system can be considered as a feedback loop that involves both discrete-time and continuous-time signals. Many feedback systems for AO systems have used classical integral feedback to measure and reduce the wavefront error. In Japan, Hida observatory has an AO system as one of the observational equipments for solar observation. This AO system also uses pure integrator compensator and is fully controlled with software in standard personal computers [3].

Although classical integral feedback of the measured wavefront works well provided in slow operating condition, increasing demand of the control performance, more sophisticated model-based control strategy is needed, and a practical AO system should be optimized to achieve its best possible performance.

Advanced control theories such as adaptive control, neural networks [4], LQG [5], H-infinity [6], H_2 [7] and minimum variance control [8] have been applied to design AO systems and these results offer high performance. However, these approaches tend to yield high-order complex controllers, and the real-time computational burden is a significant obstacle for realization of these potential performances. In addition to this, because the AO systems are sensitive to variations in atmospheric turbulence, the non-stationary characteristic of atmospheric turbulence often brings to recalculate the control algorithms, or to modify the control methods for the different atmospheric conditions and then the system must be re-optimized.

Reduced order and tunable robust control is a promising solution to overcome the dilemma. There have been many studies about robust control system design. Among them, parallel-model-and-plant paradigm, referred to as Robust Model Matching (RMM) [9-11] is considered as a natural and tractable approach to design and analysis of robust control systems.

In this paper, we have designed a robust compensator based on the RMM strategy. Our approach presents some major advances over previous controller design for an AO system. Firstly, design procedure is simple and yields low-order controllers. Secondly, robustness can be tuned easily. Thirdly, the robust compensator can be attached to any kind of existing systems.

The rest of the paper is organized as follows. In Section 2, we give the brief explanation about the AO system in our laboratory. In Section 3, plant modeling and identification of the system is illustrated. Section 4 reminded the RMM and described the actual robust controller design for the plant. In Section 5, we made the performance evaluation of the designed robust compensator. In Section 6, we gave an account of the experimental procedure of the system and analyzed the experimental results. Finally, conclusions and future works are given in Section 7.

2 AO System Description

Fig. 1 shows the AO system hardware structure, which is a simulated atmosphere-telescope system in our laboratory. It is designed to compensate for low –order turbulence in rather short wavelength and equipped to the dome-less solar telescope at the Hida Observatory in Japan. There are three units including wavefront compensation, tip-tilt compensation and observation, each of them is controlled by the respective PCs. All the PCs are connected with the LAN and controlled with a host PC.

As for the AO system is a standard closed-loop type, its simplified closed-loop block diagram can be described as Fig. 2, where CC is the control computer, which is acted as a pure integrator. DA is the digital-to-analog converter. The Wavefront sensor (WFS) digitizes the detector signals, and applies specific algorithms to derive the wavefront measurements. HVA is the high voltage amplifier, it amplify the low voltage outputs of the DA to drive the actuators of the DM.

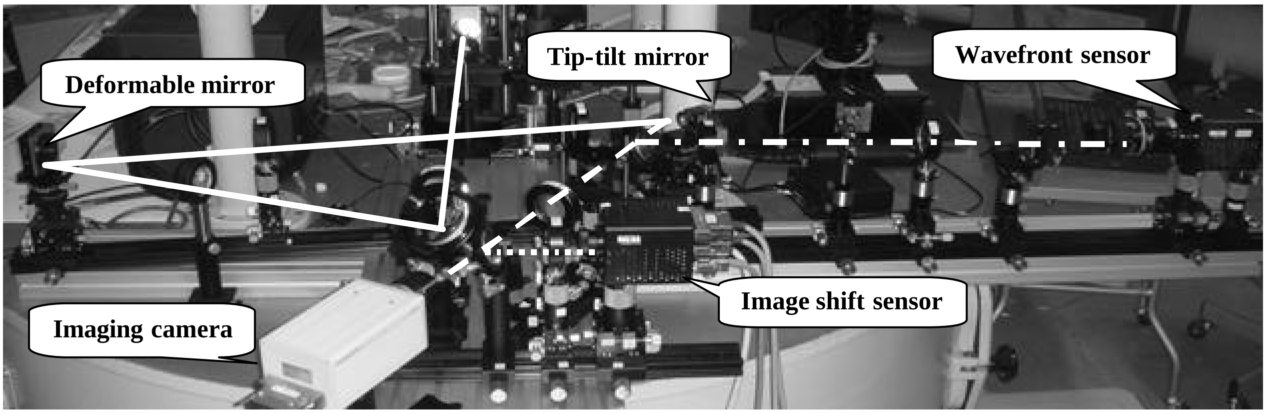

Fig. 1 AO system hardware structure

As shown in the figure, the input of the system is the uncompensated wavefront; the role of the controller is to adjust the shape of the DM canceling the aberration induced by the turbulence [12].

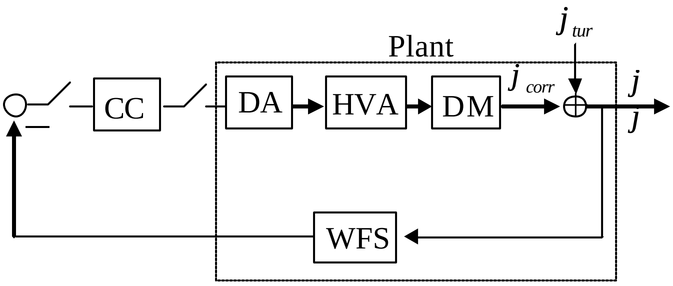

Fig. 2 Block diagram of the conventional AO system with integrator controller

3 Plant Modeling and Identification

The transfer function of the AO system is theoretically derived as Eq. (1) in [13].

$$G(s) = G_1(s) \times e^{-T_d s} = \frac{(1-e^{-Ts})^2}{(Ts)^2} \times e^{-T_d s} \qquad (1)$$

Here, T_d denotes computing time and T denotes integration time of the WFS. Considered $G_1(s)$ in equation (1), it is straightforward to show that the gain of $(1-e^{-Ts})/(Ts)$ is equal to $\sin(wT/2)/(wT/2)$ and its phase to $-wT/2$. In the low frequency domain $\sin(wT/2)/(wT/2) \approx 1$ and

$$\frac{1-e^{-Ts}}{Ts} \approx e^{-Ts/2} \tag{2}$$

which represents a pure time delay of $T/2$.

Since the integration time of the WFS is rather small, $e^{-Ts/2}$ can be assumed as unity. Moreover, as for the image processing is simple and we applied a fast algorithm in our PC-based system, the computing time is also fairly small. Therefore, the second part in equation (1) also is regarded as unity.

In order to verify our plant modeling assumption above, we have conducted several laboratory experiments and deduce practical model of our actual AO system to design robust compensator. We added stepwise input to the plant and obtained the output signals, and also calculated and made simulation of the theoretical plant model by using System Identification Toolbox in MATLAB™. Fig. 3 shows the step input responses of experimental and theoretical plant. From the Fig. 3 we can learn that the output of the theoretical plant model is approaches to the input. On the other hand, the experimental output has a vibration with a delay. We consider that it is because we simply regarded the transfer function of the experimental plant as unity and practically, there should be some differences between the theoretical plant and the experimental plant model. However, as for the delay is rather small and the system can follow up precisely to the input, we regard the theoretical and the experimental plant model is roughly the same.

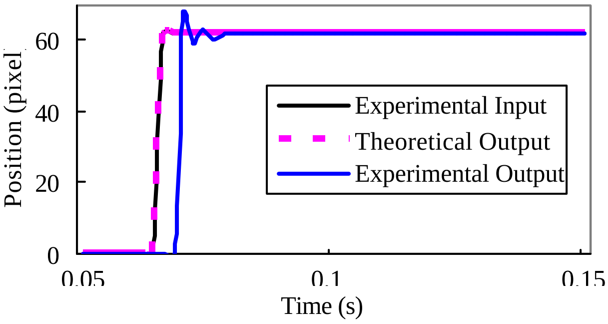

Fig. 3 Step input responses of experimental and theoretical plant

4 Robust Compensator Design

Robustness is an important subject for practical system designs based on model-based strategy. It is a significant property that allows the control system to maintain its function despite the environmental disturbances and the system uncertainties. In this section, robust model matching method is briefly summarized, and then the proposed robust AO control system design based on the method is shown.

In [14] the relation between disturbances and model uncertainties was discussed, and the Base-Equivalent-Disturbances (BED) that represent both model uncertainties and real disturbances were defined in general control scheme. Moreover, design methods of attachable robust compensators for existing control systems were also proposed. The role of the attaching robust compensator is to attenuate the affect of BED on controlled outputs. Regarding attachable compensators, both the performance and the configuration of the control system are important considerations. In this framework, new controller architecture based on Youla parameterization in Two-degree-of-freedom scheme is discussed in [15-16] and a plug-in robust compensator [17] is proposed to exploit existing controllers.

Turning now to robust control design method, a practical approach to the design of attachable robust compensators has been developed for the LTI plant. The principle behind this method is RMM, which make the input–output property of the augmented plant approaches to the nominal model, namely, the low sensitivity to external disturbance and modeling error. This objective is achieved by means of rejecting the equivalent disturbance that represents the modeling errors [18]. Also, despite the parameters of the controlled plant changes greatly, a constant control performance can be obtained by setting the bandwidth.

Summarizing the overall consideration above, we designed a robust compensator for the AO system based on the RMM strategy. The structure of robust compensator is then constructed as shown in Fig. 4. The $F(s)$ is a low pass filter that satisfies the low sensitivity as well as robust stability. Here, the low-pass filter is settled as

$$F(s) = 1000000/(s+1000)(s+1000) \tag{3}$$

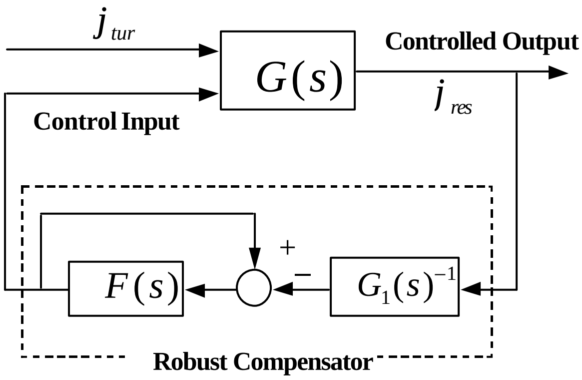

Fig. 4 Proposed robust AO control system.

Based on the transfer function of the robust compensator, we obtained the control algorithm of the compensator by Z-transform that can be expressed in the following input: $u(k)$ and output: $y(k)$ differential equation:

$$y(k) = y(k-1) + 1.25\,u(k-1) \qquad (4)$$

The proposed approach is more tractable because the design procedure is much simpler and generally solution has lower order than conventional approaches.

5 Robust Performance Evaluation

In this section, we evaluate the proposed AO system comparing with AO system with classical pure integral feedback. It is well known that robustness (disturbance attenuation) is incompatible with robust stability. We have examined the gain margin and phase margin of both control systems.

Fig. 5 shows the frequency response characteristics of open-loop transfer functions of the AO system with using pure integrator and robust compensator, respectively. The cut-off frequency for the AO system with pure integrator is about 1 rad/sec (0.16Hz) as shown in Fig. 5(a), while the robust compensator is about 899 rad/sec (143Hz) in Fig. 5(b). For frequencies lower than this cut-off frequency, the AO system is able to apply a gain in the loop and to compensate for perturbations. Comparing both characteristics, we see that the robust control system have more phase margin as well as enough gain margin, comparing with the pure integrator system. Therefore, the robust control system has the better frequency domain than the system with pure integrator.

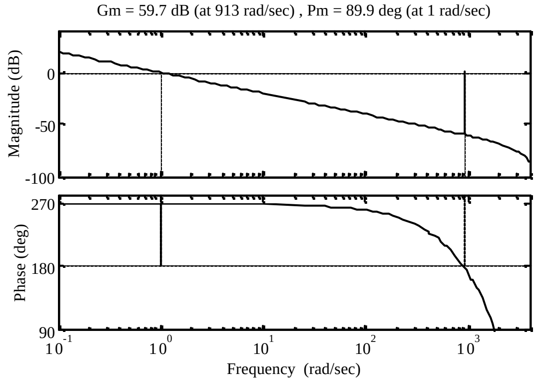

Fig. 5(a) Using pure integrator

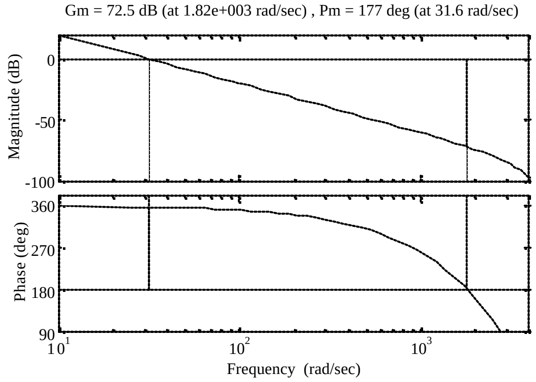

Fig. 5(b) Using robust compensator

Fig. 5 Frequency response of the system

Furthermore, in order to verify the robustness of the AO system, we introduced some noises and made simulation with MATLAB™. As shown in Fig. 6, the solid line is the Band-Limited white noise which acted as uncompensated wavefront; the dashed line and the curve line show the values of the residual phase after reducing the noise, by using pure integrator and robust compensator respectively.

As shown in the Fig. 6, the value of the residual phase is tending to be minimized instantly by using robust compensator, comparing to the use of pure integrator, which means that the AO system with robust compensator has the better robustness than the system with pure integrator.

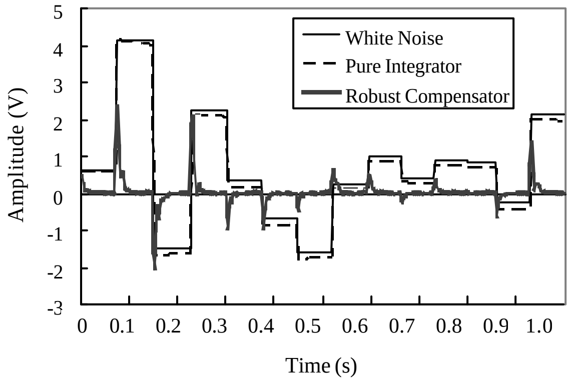

Fig. 6 Simulation results of reducing the noise

We have also compared the sensitivity of both systems. Fig. 7 shows the gain diagram of transfer functions.

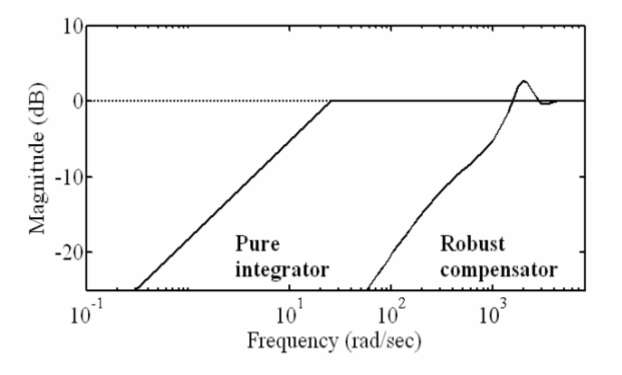

Fig. 7 Gain diagram of the AO systems

From the Fig. 7 we can learn that the robust control system have better frequency domain comparing with pure integrator system. In addition to this, the bandwidths of the proposed AO system can be easily tuned by changing the bandwidth of the low-pass filter F(s). In Fig. 7 the robust control system has an overshoot, however, the value of the overshoot is small enough and so that there are less affect to the perturbation correction efficiency of the control system.

6 Laboratory Experimentation

In order to investigate the practical performance of the AO system, the laboratory experiments were conducted. We carried out the experiments by putting the AO module behind the simulated atmosphere-telescope system. There are two driving modes for the mirror: tip-tilt and turbulence. In the tip-tilt mode, the mirror surface remains flat but inclines with a given oscillation frequency; when the turbulence mode is selected, the mirror surface is corrugated with a given frequency. These frequencies can be tuned by a parameter in the software.

In our experiment, we set the oscillator frequency in the tip-tilt mode and changed the tip-tilt frequency. Table 1 listed the results of 32, 64, 99, 130 and 172Hz. From the table we can see that with applying the AO system, by the frequency of 32, 64, 99, 130Hz, the deviations both in horizontal and vertical directions were improved significantly using the robust compensator comparing to the use of pure integrator.

Table 1 Deviations of centroid positions.

Oscillation frequency (Hz)	Without AO		With AO (pure integrator)		With AO (robust compensator)	
	Horizontal (pixels)	Vertical (pixels)	Horizontal (pixels)	Vertical (pixels)	Horizontal (pixels)	Vertical (pixels)
32	3.519353	0.169163	3.521988	0.164648	0.585902	0.106992
64			3.515884	0.155137	1.360844	0.127234
99			3.496365	0.150535	2.109017	0.167549
130			3.499584	0.15316	2.726762	0.209682
172			3.475399	0.1518	4.123651	0.237782

7 Conclusions and future work

In this paper, we have proposed a simple and practical robust compensator for an AO system which is based on the RMM strategy. As for the design procedure is simple and yields low-order controllers, there is less real-time computational burden than high-order, complex controllers.

To verify the robustness and the performance of the AO system, we conducted simulations as well as laboratory experiments. Simulation and experimental results shows that the system with the robust controller has improved considerably comparing to the previous works.

For the future work, the processing speed of the AO system should be improved in order to overcome the insufficiency of the processing speed. Moreover, adjusting the parameters of the robust compensator also is under our further consideration.

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